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Review

Anticounterfeiting and Fraud Mitigation Solutions for High-value Food Products

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ABSTRACT

Globalization and the increasing complexity of supply chains have allowed food fraud to expand to a great extent. Some of the most serious effects of these deceitful activities are damage to a brand's reputation and trust, economic losses, and public health risks. The usual victims of food fraud are dairy, meat, fish, and seafood products, as well as fats/oils and alcoholic drinks. The purpose of this review paper is to present an updated analysis of the currently available anticounterfeit technologies and their application to the four most fraud-affected food supply chains. An assessment that was conducted to determine when the adoption of a combination of technologies could enhance food safety and brand protection is also provided. The obtained results indicate that electronic and data-driven technologies (RFID devices and digital traceability systems) are still in their infancy in the food sectors that are subjected the most to fraudulent activities. Research is necessary to develop innovative digital and physical technologies to "outsmart" such fraudsters and to prevent their illicit actions in the food sector.

Contents

The production of food and beverages in Europe is not only the largest of the manufacturing industries, it is also a leading economic sector. It in fact generates about 1.1 trillion Euros in revenues per year, employs 4.5 million people, and creates an added value of almost € 222 billion (FoodDrinkEurope, 2021). Just four subsectors account for more than half of the total revenues: meat products (20%), dairy products (15%), beverages (14%), and baked/farinaceous products (11%). A factor that is linked to the success of the European food sector is the abundance (1,463) of recognized quality-certified agri-food products labeled as Protected Designations of Origin (PDO), Protected Geographical Indications (PGI), or Traditional Specialty Guaranteed (TSG). Although quality and value are recognized through awards and ratings in the US, these designations are the critical marks of excellence that boost the market value of European products.

Italy is the European Country with the largest number of certified products (845), followed by France (698), Spain (349), Greece (261), and Portugal (184), and these products are significant drivers of the positive economics of the Italian food sector. Indeed, Italy produced a combined total of 19.1 billion Euros in PDO and PGI products in 2021, which represented a 16.1% increase over the prior year. The geographically recognized food products sold across Europe include 244 cheeses, 199 meat products, 399 horticultural products and cereals, and 143 oils and fats. In Italy, cheeses, of which there are 56 registered products, contribute the most to Italy's PDO, PGI, and TSG food

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productions, with a total value of 4.68 billion Euros (+12.8% compared to 2020) (Ismea, 2022).

Globalization and the increasing complexity of agri-food supply chains have amplified food fraud activities. Although the high-quality, high-value food industry has always been a target of fraud, these illicit schemes have expanded so much that they have been estimated to cost the global food industry as much as 30 billion Euros annually (European Commission, 2018). Such activities are not limited to developed countries; Gwenzi et al. (2023) has recently reported on the lesser-known, but highly impactful, food malpractice and fraud that is occurring in low-income countries due to inadequate border controls. Moreover, food fraud does not just result in financial losses for the industry alone. Its potential to raise the risks of public health is well known (Spink & Moyer, 2011), as is its potential to cause financial losses for consumers through packaging fraudulence.

Food fraud has not been officially defined in the EU, although it has been discussed in the literature and defined by standard-setting organizations and regulatory bodies, which tends to sow confusion (Popping et al., 2022). The FDA in the USA refers to Economic Motivated Adulteration (EMA), a phrase that is often used as an alternative to "food fraud" (Everstine et al., 2013). It is widely agreed, irrespective of the terminology, that financial gain characterized by intentionality is the most common motivator of food frauds (Robson et al., 2021).

Over the years, food frauds have been categorized both broadly and narrowly. Spink et al. (2013) defined seven fraud categories that are particularly useful as they coincide with how and when food fraud occurs along the supply chain (Table 1). For example, the "counterfeit" category refers to fraudulent activities that are aimed at making a food product, with a certain composition, appear different from what it is, or at realizing a product from scratch that resembles a real one. The deception can be explicit, that is when the label bears false statements, or implicit if the packaging, shape, and/or branding confuses the customer, even when a false declaration is absent. Counterfeiting also implies that false data have been affixed to a food product or to its packaging. These actions infringe product authenticity, for example, through the use of improper trademarks or PDO, PGI, and TSG falsifications. The authenticity of a product may refer to both originality, in relation to the manufacturer or brand of origin, and integrity, which means that it has not been tampered with, altered, adulterated, mislabeled, or counterfeited at any point along the supply chain. Thus, anticounterfeiting solutions should guarantee reliability in the protected product sector where the geographical-origin credential is highly valued, or the image of a product may be tarnished.

In order to limit the economic losses from food sector fraud, prevention and mitigation countermeasures are adopted to protect food supply chains (Robson et al., 2021; Popping et al., 2022). The aim of this survey is to review the existing anticounterfeiting technologies and mitigation strategies adopted to prevent supply chain fraud that results in economic loss or which damages the reputation of a brand. Each technological solution, whether classified as mechanical, electronic, marking, or data-driven, has been assessed for application and use in specific food subsectors. In addition to preventive and hindering strategies to counteract food fraud, several physico-chemical analytical methods exist for the *a posteriori* authenticity control of finished products. However, these strategies are not deeply discussed herein as they are somewhat complex and deserve a detailed analysis.

This review paper is organized into four sections: Section 1 analyses the main types of fraud on the food products market, Section 2 compares and contrasts the technologies adopted to limit counterfeiting activities, Section 3 explores the most food fraud-affected supply chains (milk and dairy products, meat, fish and seafood, wines and spirits, and olive oil) to identify the best anticounterfeit solutions to adopt, and Section 4 presents the concluding remarks.

Table 1
Different types of food fraud (Spink et al., 2013).

Term	Definition
Adulterate	A component of a legitimate finished product is fraudulent
Tamper	A legitimate product and package are used in a fraudulent way
Over-run	A legitimate product is made in excess of the production agreements
Theft	A legitimate product is stolen and passed off as legitimately procured
Diversion	The sale or distribution of a legitimate product outside the intended markets
Simulation	An illegitimate product is designed to look like but not exactly copy a legitimate product
Counterfeit	All aspects of a fraudulent product and package are fully replicated

Anticounterfeiting and fraud mitigation solutions and technologies

Anticounterfeiting technologies can be subdivided into five categories on the basis of their usage features. Overt anticounterfeiting solutions that incorporate visible features, such as distinct marks or labels, are crafted using specialized techniques that present significant hurdles for their reproduction. To foster consumer awareness, their application necessitates that the methods ensure conspicuous indicators of their removal or reuse. Packaging security, augmented with overt features to reveal evidence of tampering, can promptly flag unauthorized access attempts and bolster product integrity (Zadbuke et al., 2013). Such packaging types as vacuum packs, film wrappers, or heat-sealed trays inherently possess tamper-evidence attributes. On the other hand, covert security solutions are targeted to brand owners and stakeholders to allow them to detect counterfeited products, while remaining imperceptible to end-users who lack the tools for their verification (Jotcham, 2005). Their efficacy hinges on being inherently challenging to detect or replicate without specialized knowledge (Shah et al., 2010). Furthermore, forensic markers include solutions that are concealed within the packaging or products themselves, which require sophisticated scientific methodologies for their detection and authentication.

However, a proactive shift from reactive to preventative food control measures is imperative to minimize both the economic and safety ramifications of food fraud. Track and trace technologies, coupled with supply chain vulnerability analyses, serve to mitigate food safety and food fraud risks. The subsequent sections delve into anticounterfeiting and fraud mitigation solutions that have been categorized by their distinctive technologies: mechanical solutions, marking technologies, traceability, electronic identification, and blockchain.

Anticounterfeiting mechanical solutions. Mechanical anticounterfeiting technologies leverage on authentication of the material properties or, when they are integrated with unique codes, have identification and tracking purposes. Labels, seals, and antialteration devices fall into this category.

- *Labels*. Food products often bear more than one label to meet the mandatory, voluntary, and advertising requirements. Commonly printed labels, though easily replicable due to uniform patterns and ease of decoding (Liu et al., 2019), can be combined with digital printing for product serialization purposes to enhance security. Anticounterfeiting labels should feature physical unclonable functions (PUFs) or be combined with other security elements, such as unique identification codes, trademarks, or covert technologies (Liu et al., 2019; EUIPO, 2021). Adhesive labels are fundamental for packaged foods as they can contain embedded security devices (either printed on the top surface or added to the adhesive layers). For example, ultra-destructible labels are adhesive labels that are composed of ultra-brittle materials and very resistant glues that make them impossible to remove from a surface in a single piece (Patel et al., 2020), thus preventing unauthorized label transfers and acting as tamper-evident devices. VOID labels are security labels with tamper-evident features; they contain hidden texts or images that become visible when the label is removed. The ease of customization ease has allowed these devices to be used globally in a variety of sectors (Zadbuke et al., 2013). When selecting a label type, it is crucial to consider the overall cost of the solution, which is influenced by several factors, including the costs of the label materials (paper, plastic, adhesive, opaque, etc.), the capital investment for the production line equipment, the cost associated with the printing process (which is influenced by the number of colors), and the hourly running cost of the label production line (Fairley, 2013). Although basic adhesive labels are cost-effective (a few cents per unit), security labels containing some of the features mentioned above can be more expensive, especially because of the costs of the specialized materials involved in composing security elements. In this case, more-secure labels are reserved for high-value products (ICT or clothes) rather than widely consumed foods.

- *Seals.* Seals are physical devices that are used to guarantee the integrity and authenticity of products, to hinder counterfeiting, and to make any attempt of tampering evident. The seals for beverages range from breakable caps and plastic and/or metal cap wrappers to security-ringed screw caps (Kutluğ et al., 2020). Transparent shrinkable plastic films are also often used to envelop bottles and jar closures, especially for pharmaceuticals (Zadbuke et al., 2013). The devices used for food products include warranty seals, adhesive paper strips applied to the package closure and container side (jars or bottles), metal/plastic rings tightened around bags/pouches, and aluminum snap buttons (for butter packs). Cost-effective and multi-functional seals serve various purposes apart from security (protection, packaging, and even marketing).

- *Antialteration devices*. Antialteration devices are physical objects that mechanically make it impossible to counterfeit a product in its original packaging. An antirefill cap is one of the most common systems in this category; it is usually made of plastic material and designed to be inserted into the neck of bottles. It generally consists of one or more ball valves that allow the liquid to leak out and, in parallel, impede the bottle to be filled with the same liquid or with an unauthorized one. The use of these caps is compulsory in some cases. From an economical point of view, assessing the costs of antialteration devices is challenging as they depend on several factors, including the type of device, the compositional materials, and the complexity degree of the technology (EUIPO, 2021).

Anticounterfeiting marking technologies. Anticounterfeiting marking technologies entail the use of marking security elements (e.g. texts, codes, and graphic motifs) mainly for authentication purposes. Marking technologies can also be used to track products along the supply chain when they contain or are made up of a unique identifying code. The security of the solution relies primarily on the nature of the used technology. Machine-readable codes, holograms, inks, watermarks, microtexts, and laser coding all fall into this category.

- *Machine-readable codes*. Barcodes are graphic elements that encode a variety of information, such as unique identification codes or product-related data, that can be read automatically by means of optical scanners. Bidimensional barcodes (Quick-Response codes or Data Matrix) can carry more data than 1D barcodes and can enable the final consumers to authenticate products, even through the use of smartphone applications (Soon & Manning, 2019). According to Xie et al. (2015), although barcodes are characterized by high accuracy and reliability, a high speed of reading, and cost-effectiveness, they are vulnerable to replication. In order to improve the security of barcodes, they can be combined with Copy Detection Patterns (CDPs), which are noisy maximum entropy images. Printable on various document types, they rely on the "information loss principle", whereby each print-and-scan process causes a loss of information as the image morphs in structure and quality. Authentication is determined by the amount of information found by a CDP detector (Khermaza et al., 2021).
The remarkably low cost of machine-readable codes explains their widespread use, not only for identification but also for logistics, traceability, and marketing purposes. A true cost tally of such a system should include the fixed and variable costs of software, hardware, and, eventually, databases to manage digital fluxes when barcodes and Quick-Response (QR) codes are used for electronic labeling. Among the disadvantages of the use of 1D and 2D readable codes in the food sector is that good optical transmission can be difficult for moist, cold/frozen, or irregularly shaped products (Kumperščak et al., 2019). However, machine-readable codes can be very small and can also be directly printed onto the packaging (e.g. on bottles, jars), thereby allowing the environmental impact of labeling to be reduced.

- *Holograms.* Diffractive Optical Variable Image Devices (DOVIDs), which consist of stereoscopical images that are visually different under changes in lighting and when they are viewed from different angles, are prevalently used for document security and brand authentication purposes (Andrulevičius, 2011). Holograms, being an overt technology, are easily identifiable by inexpert users without the need of special tools. However, like CDPs, the variable appearance of holograms renders them nonreproducible and duplicable for commercial scanners or photocopiers (Ping & Yang, 2019). The cost of holograms mainly depends on their features and on how they are applied to the product: if they are purchased as predefined stickers without customization, their price is relatively low, while their cost can increase when customization is requested (e.g. embedding of a company's logo, the printing of specific product codes), thereby limiting their adoption for affordable food products (Sohail et al., 2018). However, because of technological progress and lower costs linked to mass production, the application of holograms for anticounterfeiting in the food sector is expected to increase.
- *Inks.* Covert security inks that are sensitive to ultraviolet (UV) or infrared (IR) light are already used for authentication and counterfeit prevention purposes for passports, banknotes, and tickets, and they could also be used in the food sector to print barcodes or other elements on labels (Hersch et al., 2007). These inks create three hurdles for fraudsters as they are difficult to find on the market, expensive, and invisible in daylight, and are therefore impossible to photocopy or scan. An emerging type of security inks is luminescent taggants, such as organic dyes and quantum dots (QDs). They were developed for use as anticounterfeiting inks because of their versatility in generating customized marks and codes on different substrates. Research into the limitations of durability and toxicity, for both humans and the environment, has resulted in new luminescent ink materials that are able to overcome these issues. Ngoensawat et al. (2021) studied and created a nanohybrid bacterial cellulose nanocrystal (BCNC) and UV-responsive ZnO QD anticounterfeiting ink that is water-resistant, nontoxic, biodegradable, and eco-friendly. Thermochromic inks, which are composed of pigments that change color as a result of temperature variations, constitute a third type of ink that can be used for monitoring the food cold chain. They function by indicating whether a product has been maintained at the correct temperature or has been exposed to cumulative temperature abuse (Soon & Manning, 2019).
A key aspect pertaining to the applicability of using anticounterfeiting inks, especially in the food sector, is the need to determine their printability on the substrate that has to be used. Because of the high toxicity of security inks (Yuan et al., 2021), none of them can be applied directly to any portion of edible foods or on

permeable substrates. The durability of the used ink also needs to be tested for products with a long shelf life, which are manipulated extensively along the food chain and are often stored at low temperatures or under humid conditions.

- *Watermarks.* Watermarked paper traditionally contains embedded graphics, images, or texts that are only visible when the paper is looked at under a backlight, and it is used to ensure the integrity of high-value documents (banknotes, certificates, etc.). Although specialized equipment and personnel are needed during the production of watermarked paper in mills, it is generally inexpensive (Soon & Manning, 2019).
  Today, digital watermarking relies on computer algorithms to produce texts or invisible coded images that can be introduced into documents or labels. These digital watermarks can be automatically linked to mobile apps to guarantee originality and/or a lack of alteration, and they can even be linked to the Internet to obtain access to multimedia contents (Xuehua, 2010; Del Mastio et al., 2016).
- *Microtexts*. Microtexts are covert security elements that consist of extremely tiny texts, codes, or images that are embedded in larger visible writings or pictures. This technology is mainly used for authentication purposes because it is very difficult to duplicate without resorting to advanced printing technologies and because, being hard to detect, potential fraudsters are unaware of its presence (Soon & Manning, 2019).
- *Laser coding.* The laser engraving technique involves the use of a laser beam to permanently mark texts, codes, images, or logos on various kind of materials and objects by removing material layer-by-layer. This method is applied for different purposes in many industrial sectors, including the incision of serial numbers on electronic devices (Agalianos et al., 2011). The food sector also uses it to etch identification codes into packaging and even into the food products themselves for traceability purposes. Chen et al. (2009) showed the possibility of replacing ink printing to code eggs with a pulsed CO_2 laser marking system, while Henze et al. (2015) proved that laser-cut codes could be engraved into vegetables, bread, and fruit.
  However, two issues must be overcome before laser coding can be applied directly to edible food: etching damage may compromise the shelf life of a product by favoring water loss and promoting oxidation and browning (especially in fruit) and wounds may make food more prone to microorganism contamination (Sood et al., 2009).
  Estimating the actual costs associated with this technology is a challenging task for several reasons. However, it can be assumed that the costs mainly depend on the equipment that has to be implemented on the production line, the type of used laser technology, and the costs linked to energy consumption.

Traceability-based anticounterfeiting methods. Mid and long-term analyses used to predict and prioritize the risks related to food fraud are necessary for both from industries and regulatory bodies to prevent and mitigate the economic and safety impacts of food fraud events (Butler et al., 2021). This concept opens the way toward a new science topic that is related to finding tools and plans for vulnerability assessments. An analysis of the whole value chain to assess its vulnerabilities would allow food companies to adopt solutions and strategies to prevent or limit fraudster activities. Research plans and certification bodies (e.g. BRC, GFSI, CEN, ISO) have developed and promoted food fraud vulnerability assessment methods (FFVA), specific tools, and guides to evaluate food fraud vulnerability for different food sectors and firm sizes. The vulnerability degree of a company can be reduced by adopting fraud-proof information and documentation systems, automated data capturing, and mass balance verifications of ingredients and products in both the company and at the suppliers (Barrere et al., 2020; Robson et al., 2021).

The digitalization of food supply chain traceability increases the availability of data stored in different registries, web portals, and information exchange platforms, which, in turn, allow supply chain fluxes to be analyzed in real-time, by means of text mining and artificial intelligence (Bouzembrak et al., 2018). The availability of smart systems that can be used to manage large datasets in order to perform a horizon scanning of the threats which can emerge in particular political, geographical, and economic situations, allows the likelihood of the occurrence of a fraudulent action to be evaluated along extended and complicated supply chains.

Traceability involves resorting to a means that allows a single product to be unequivocally identified, mainly by assigning a unique serial code to it, which is recorded throughout the entire supply chain, from the producer to the consumers. However, since the codes can still be copied or falsified, security systems have been found to identify duplicates or void codes, e.g. using randomly generated codes through highly secure algorithms or cryptographic systems (Soon & Manning, 2019). The limits of traceability systems are related to the connection of the physical object to the device that contains the unique code, which may be applied incorrectly or fraudulently manipulated. Therefore, technologies that enhance the identification reliability have been envisaged (electronic identification) and the protection of the digital traceability should be improved by means of ICT technologies (e.g. blockchain).

Electronic labeling and identification. Electronic technologies involve the coupling of goods with unique identification devices that can store information or can provide their authentication. RFID (Radio Frequency Identification) and NFC (Near Field Communication) systems are wireless devices that allow contactless information transmission through electromagnetic waves. A tag, which is applied to the product, contains an Integrated Circuit (IC) that can be re-writable, which allows the stored information to be updated along the product supply-chain path. RFID devices, which have already been successfully employed in other sectors (Cole & Ranasinghe, 2008), can be exploited for many purposes in the food industry, although the high cost and drawbacks related to their low readability, due to the composition of food and packaging, have limited their mass-scale adoption (Barge et al., 2019). NFC devices, which operate over a short range (4–10 cm), can be successfully used in contact with different materials, such as paper, plastic, or glass, although they may be less efficient if placed in contact with metal or moist surfaces.

Authentication can be performed, by means of RFID tags, both online and offline. In the online mode, the reader is assumed to be continuously connected to a backend system of the reader, e.g. to acknowledge a unique number being stored in a database (Kardaş et al., 2012) or shared on a distributed ledger as a blockchain. Offline systems instead allow tags to be authenticated without continuous connection to the web or to a central private ERP database.

In order to be successful for security purposes, RFID tags have to be resistant against a variety of attacks. It is necessary to find solutions to prevent cloning and duplication of the tags, such as encrypting the stored information and only making it accessible through passwords or private keys, and preventing their transfer, for example by embedding them in the product or in the packaging so that they are poorly visible and difficult to manipulate, and so that any eventual breakage of the packaging is clearly visible to the consumers. In some anticounterfeiting frameworks, RFID and NFC tags carry identification codes and encrypted keys that allow authentication to be made by means of specific algorithms (Jiang, 2017). Physical Unclonable Functions (PUFs) have been proposed to store secret key material in a tag (Tuyls & Batina, 2005).

However, NFC tags can be subjected to different counterfeiting attacks, such as the modification of the product-related information stored in a tag, the cloning of tag data related to an authentic product onto tags placed on counterfeited items and/or the removing of a licit tag from an original product and its transfer to a fake one (Alzahrani & Bulusu, 2018). NFC tags allow consumers in possession of NFC readers (e.g. enabled smartphones) to play an active part in the anticounterfeiting strategy, as they can autonomously identify and authenticate the products at the point of sale, thereby detecting counterfeited goods. In addition, the NFC technology is becoming an essential tool for proximity marketing as it can carry advertising contents and enhance the purchasing experience (Gajanova et al., 2019).

Special electronic seals, based on RFID technology, have recently been developed. These devices, which are also called "tamper tags", combine the features of simple NFC tags with the features of tamper-evident seals (Barge et al., 2020). They are composed of a simple NFC tag, whose antenna has a loop filament. These devices can be used for many different applications, such as in luxury goods, pharmaceutical products, and others. These seals can be used in the food and beverage sector for the protection of fine drinks, wines, and spirits: they are applied to the bottles with the NFC tag placed above the cap, with its antenna loop going down along the neck. If the loop of the tag is intact (the product has not been tampered with), then the information stored in the memory of the NFC tag is shown to the consumer to prove the authenticity of the product, while, in the case, the product has been opened or tampered with, the loop is damaged, and the tampering attempt is permanently stored in the memory of the chip. In this case, when the NFC tag is scanned, an error message appears; moreover, tampering is clearly visible because the seal is broken. This system constitutes a powerful anticounterfeiting tool since it allows a product to be identified as original in both its physical and digital dimensions.

The cost of this solution varies depending on the kind of tag, the type of materials used for its construction, on its dimension, and on the purchased quantity. In general, tags are affordable as they cost just a few cents per unit. Moreover, the costs also depend on the system that is used for the recording and storing of product information in the tags (EUIPO, 2021).

An important drawback of using RFID is that tags, due to their electronic nature, should be disposed of as special waste. Research in this field has recently focused on the development of sustainable tags; Moras et al. (2021) presented a recyclable chipless RFID tag printed with an organic ink on a paper-based substrate. Chipless RFID tags, which shift the complexity of the technology to reading systems, make it possible to produce eco-friendly labels that are easy to dispose of. However, further research is needed in this field, especially considering techniques to print tags on innovative substrates. Chipless RFID tags could in fact be designed on any material or substance, such as animal or plant tissues (Ali et al., 2023).

Electronic labeling, which involves the communication of product information by means of web-based digital systems, can also be performed through the use of bidimensional barcodes. The increasing willingness of producers to adopt e-labels is proven by the fact that government agencies are issuing new rules to regulate their adoption in different sectors. Since 2023, Europe has regulated the electronic labeling of the wine and spirit sector with EU Reg. 2021/2117 (European Union, 2021). Moreover, the adoption of e-labels bearing a QR code on the tax stamps of alcoholic beverages has been made compulsory in Mexico (Estados Unidos Mexicanos, 2021). In the US, bioengineered food has required a specific disclosure since 2019, which can be made by means of electronic or digital links (US Department of Agriculture, 2018). Moreover, the Russian Chestny ZNAK (Honesty Sign Product), a track and trace digital system, was put into effect to guarantee the authenticity and declared quality of goods purchased by Russian customers (Russian Federation, 2017). Moreover, e-labels with a data matrix code that conveys such information as serial numbers with a crypto code, the batch numbers, the production and expiry dates, are mandatory for dairy products, honey, and mineral water, especially when they are imported into Russia. As demonstrated by Lombardi et al. in 2017, the increasingly positive approach of consumers to the use of mobile devices during shopping positively influences their willingness to pay for a QR code-labeled product.

It is possible to hypothesize that companies prefer using bidimensional barcodes to RFID/NFC tags for more affordable products; this is because they are easier to print and apply and, even more importantly, they are cheaper. However, certain companies might prefer to use tags on high-value products, since they suggest major protection and their cost is negligible on the final price of the product.

Blockchain. Product information and identification data can be protected using the blockchain technology. Blockchain is a distributed database that is shared among several nodes on a peer-to-peer network. Data authentication involves the consensus of a sequence of chained blocks containing timestamped transactions that are protected through public-key cryptography and verified by the network participants. The information contained in a block, once validated, cannot be modified later, and this makes the blockchain a secure system (Seebacher & Schüritz, 2017). As the information is kept in a shared ledger, there is no centralized data storage system. Data can be archived, after their authentication, in either a private blockchain or in a local database. All the data are then stored off the chain in a distributed peer-to-peer system and the hashes of the data are recorded on the public Ethereum blockchain to ensure immutability. Blockchain sustainability is affected to a great extent by the high energy consumption required to store the shared ledgers on several distributed computers. Moreover, additional costs are related to the mining process, as each transaction fee amounts to 0.02 Euros.

The blockchain features of decentralization, security, and data immutability are regarded as powerful drivers for the improvement of transparency, trust, and reliability in sharing information among numerous players in complex systems, such as an agri-food supply chain; for this reason, the blockchain is also emerging as an anticounterfeiting tool, since it allows different supply chain stakeholders to quickly and precisely track the history of a product, from its origin to its final destination, thus preventing and contrasting any fraudulent activity at each point of the chain (Seebacher & Schüritz, 2017; Cena et al., 2019). Although blockchain guarantees the integrity of the digital representation of an item, it cannot ensure parity with the physical item in the absence of other combined identification techniques (e.g. RFID, barcode, QR code) (Lo et al., 2019).

The deploying of the blockchain technology to improve the performance of food traceability has not yet been fully investigated (Feng et al., 2020). However, some papers concerning the suitability, sustainability, and the boundary conditions necessary to apply blockchain to monitor and the manage some agri-food supply chains have been published (Behnke & Janssen, 2020; Ehsan et al., 2022).

In addition, according to Singh et al. (2023), even though the benefits of the blockchain technology in strengthening the information security and resilience of the supply chain are widely recognized, there is still a lack of research on the contextual factors that affect its adoption and on the consequences on the key performance parameters. Therefore, future research should be focused on these aspects.

Anticounterfeiting in food supply chains – case studies

The food products and beverages that are most often affected by frauds are dairy products, meat products, fish and seafood, alcoholic drinks, and fats and oils (Soon & Wahab, 2022). Table 2 summarizes the main anticounterfeiting technologies used in each of these sectors.

The increased demand for food and the suspension of private and public-sector food inspections and audits during the COVID-19 pan-

Table 2
Summary of the main anticounterfeiting technologies used in the food sectors affected the most by fraud events.

Technology		Milk and dairy products	Meat and meat products	Fish, seafood, and their products	Wine and spirits	Olive Oil
Track and trace technologies	RFID/NFC	* Regattieri et al. (2007); Pérez-Aloe et al. (2007); Papetti et al. (2012); Magliulo et al. (2013); Barge et al. (2014); De las Morenas et al. (2014); De la Vara Martínez et al. (2018); Pearson et al. (2019); Wang et al. (2020); Zhang et al. (2020)	* Caja et al. (1999); Caja et al. (2005); Barge et al. (2015); Rejeb (2018a); Kamath (2018); Barge et al. (2020)	* Hsu et al. (2008); Kresna et al. (2017); WWF (2018)	* Sun et al. (2019); Identiv (2022)	* Conti, 2017; Papaefthimiou et al., 2017; Rejeb, 2018b; Violino et al., (2020)
	Blockchain	* Kasten (2019); Casino et al. (2020); Rambim & Awuor (2020); Tan & Phạm Thi (2020); Wang et al. (2020); Niya et al. (2021)	* Rejeb (2018a); Kamath (2018)	* WWF (2018); Khan et al. (2022); Wang et al. (2022)	* Biswas et al. (2017); Sun et al. (2019); Danese et al. (2021); Singh et al. (2021)	* Arena et al. (2019); Alkhudary et al. (2022); Fernandes et al. (2022)
Mechanical solutions	Seals			* Lewis & Boyle (2017)	* IPZS (2015)	* Limbo et al. (2014)
	Antialteration devices				* Kutluğ et al. (2020)	* Gazzetta Ufficiale della Repubblica italiana (2014); Limbo et al. (2014)
Marking technologies	Machine readable codes	* Magliulo et al. (2013); Tarjan et al. (2014); Caldarelli et al. (2020); Tan and Phạm Thi (2020)	* Rejeb (2018a); Barge et al. (2020)	* Lewis & Boyle (2017); Xiao et al. (2017); WWF (2018)	* IPZS (2015); Popović et al. (2021)	* Abenavoli et al. (2016); Guido et al. (2020); Violino et al. (2020)
	Holograms	* Carrola et al. (2014)			* Vacariu et al. (2018)	
	Inks				* IPZS (2015); Popović et al. (2021)	
	Watermarks				* IPZS (2015); Del Mastio et al. (2016)	
	Microtexts				* IPZS (2015)	
	Laser marking	* Fukuchi et al. (2012)				

demic could have favored the increase in food fraud (Brooks et al., 2021).

Milk and dairy products. Milk and dairy products are among the food categories affected the most by fraud. The main types of fraud against these products are adulteration, fraudulent documentation (mislabeling), tampering, and counterfeiting, as reported in the 2018–2021 monthly summary reports published by the European Commission.

As for many other food items, criticalities arise for dairy products when they are sold bulk or portioned because of the high risk of losing the traceability. However, they are generally packed to guarantee their physical and mechanical protection as well as to maintain their quality properties and shelf life. As the compositional characteristics, storage conditions, consistency, and shape of dairy products may be particular, different materials and packaging forms are necessary. Some packages themselves already constitute a physical barrier against product tampering (e.g. sealed plastic trays, vacuum bags).

Mechanical and marking solutions are mainly adopted to contrast and detect frauds in the dairy industry. Although paper labels are the cheapest and most diffused means of identification and of information communication (Aggarwal & Langowski, 2020), some dairy producers use holograms to protect and authenticate their products. For example, the Portuguese Serra da Estrela PDO cheese consortium applies holograms to their labels in the form of stickers as a guarantee of origin and brand authenticity (Carrola et al., 2014).

The laser engraving technique is used to permanently mark cheese products (Fukuchi et al., 2012). However, other engraving technologies are more widespread for this sector, such as the fire branding that is used for "Parmigiano Reggiano" and "Grana Padano" PDO cheeses to print, on the rind, the mark of the Consortium for the Protection that qualifies the cheeses. In addition, marks are also impressed during the forming phase through molds on the heel of the cheese wheels (EU, 2011; EU, 2018). In the dairy sector, QR codes on the labels of milk bottles and packed cheeses are often exploited. Tarjan et al. (2014), for example, proposed using QR codes together with digital traceability for yogurt.

In the last few years, many studies have been carried out on the integration of innovative digital traceability systems for dairy products, such as blockchain, RFID labels, and/or QR codes as well as other ICT solutions (Pearson et al., 2019). Magliulo et al. (2013) created an ICT-based system that integrates the use of RFID, or NFC tags, and QR codes to track and trace the "Fior di latte Napoli" cheese. Instead, Caldarelli et al. (2020) analyzed a case study of the Italian "San Rocco Dairy" cooperative which, in 2018, began to adopt the blockchain technology and QR codes to track and trace "Asiago" PDO cheese. Tan and Phạm Thi (2020) also investigated the combination of blockchain with QR codes for the entire dairy supply chain traceability in Vietnam, from milked milk to finished products. Casino et al. (2020) instead proposed a system that employed an Ethereum-based blockchain with functional smart contracts for both food products and process traceability in a Greek dairy company. Niya et al. (2021) developed a blockchain-based traceability system for the Swiss dairy supply chain. Wang et al. (2020), instead, proposed using the Hyperledger Fabric blockchain platform, paired with RFID identification, to trace milk from the production to the sale. Rambim and Awuor (2020) explored the use of a blockchain-based platform (Milk Delivery Blockchain Manager) for the permanent registration of the quantity and quality of milk delivered by smallholder farmers of Kenya to local milk collection centers. This system was proposed in order to substitute paper registers, often prone to forging with potential underpayments to farmers.

The blockchain technology can be also used to manage securely data and information resulting from milk laboratory analysis, as demonstrated by Kasten (2019). De las Morenas et al. (2014) developed a system to track milk samples, by means of RFID, from the collection to the analytical phase. An RFID reader and a GPS unit were integrated in the chilling system to record information related to the identification of the inserted samples, their geographical coordinates, and a timestamp related to the opening and closing operations. Similarly, De la Vara Martínez et al. (2018) proposed a system that integrates both RFID and GPS sensors for the traceability of milk samples used in quality control, particularly to monitor their temperature, path, and time elapsed from collection to analysis.

The identification of entire cheese wheels by means of RFID tags and their application to improve dairy traceability have been widely investigated over the years, as demonstrated by the large number of studies published in the literature (Pérez-Aloe et al., 2007; Papetti et al., 2012; Barge et al., 2014; Zhang et al., 2020).

Regattieri et al. (2007), for example, proposed an innovative framework for the traceability of the "Parmigiano Reggiano" PDO cheese. The novel solution is based on the application of RFID tags, which contain information on the production process, to the cheese wheels. The data in the tags are automatically registered in a database before the cheeses are portioned. After the portioning, an alphanumeric code, associated with the specific database record, is reported on the label of each slice of cheese. This system is of significant interest as it is a possible solution to the problem of interrupted traceability for dairy products sold over the counter that are portioned at the time of buying.

Future research should be focused on innovative methods to maintain traceability when dairy products are sold bulk. Digital techniques and Artificial Intelligence could be useful tools for this purpose as they facilitate the swift identification of fraudulent activities and automatically highlight anomalies in the data flux, thereby enabling operators to promptly take action; their application therefore deserves further investigation. Moreover, additional studies should be conducted on the effects of laser engraving techniques on dairy products (e.g. heat damage, and the effects on shelf life); laser etching, in fact, could be a powerful instrument to directly label cheeses, thus substituting the generally used printed labels and possibly reducing packaging wastes.

Meat and meat products. Adulteration and mislabeling have been reported to be very frequent frauds in developing and developed countries in the meat sector (Uddin et al., 2021). For example, illegal manufacturers try to substitute high-priced meats partially, or even entirely, with low-priced ones and then deliberately paste falsified labels deliberately before selling such products to consumers (Hellberg et al., 2021). This raises concerns regarding food safety (the presence of allergens, toxic compounds, microbial contamination, etc.), human health (the change of nutritional values), and the disregarding of diet restrictions related to religion (e.g. for Muslims, Jews, Hindus). Species substitution is very frequent, even with wild species or inedible meat that has not undergone quarantine inspection. The substitution of a high-value/quality meat with a lower-quality one also concerns the inclusion of organ meats (e.g. heart) instead of skeletal muscle in ground meat (Kozan et al., 2013). The commercialization of sick animals, stolen livestock, and illegally slaughtered animals has also been observed. Artificial color enhancement, water addition, and the use of weight enhancers are examples of counterfeiting methods used to obtain illegal profits in the meat sector. As a consequence of adulteration, meat could contain such hazardous components as steroids, phenylbutazone, and nonsteroidal veterinary drugs (e.g. from racing horse meat) (Visciano & Schirone, 2021). As meat prices also depend on certain quality and imperceivable attributes, fraudsters can also substitute and mislabel different meat breeds or meat obtained from techniques that enhance the price (no Genetically Modified Organisms (GMOs), antibiotic-free, kosher etc.). For example, the main authenticity concerns for Muslim consumers, pertaining to meat and meat products, include pork substitution, undeclared blood plasma, the use of prohibited ingredients, pork intestine casings, and nonhalal slaughtering methods.

A number of papers that deal with new analytical methods for the meat of different species and breed authentication have been published in the literature. These methods involve highly sophisticated technologies from different fields, such as chemistry, biochemistry, microbiology, morphology, spectroscopy, proteomics, genomics, etc. (Rahmati et al., 2016). These techniques, which are crucial as they are highly reliable and can be used in forensic debates, are executed in specialized laboratories and are often destructive and expensive, and thus cannot be applied to large-scale controls.

Among the nondestructive anticounterfeiting techniques, image classification, by means of convolutional neural networks, has been proposed by Kointarangkul and Limpiyakorn (2021) to identify beef from particular breeds characterized by intense marbling (e.g. Wyagu). Lo et al. (2019) proposed a machine-learning method to classify beef types, with the aim of distinguishing grain-fed beef from grass-fed beef. Track and trace technologies (Denyingyhot et al., 2022), eventually combined with optical codes or electronic identifiers (RFID and NFC) (Barge et al., 2020), can be used to trace meat information (e.g. the lot number, the package weight, nutritional values, cooking instructions, the link to the manufacturer's website, etc.) from farm to fork, by applying RFID to the cattle (Caja et al., 1999; Caja et al., 2005), to carcasses during the slaughtering phase, and to packed processed meat of different species (Barge et al., 2015; Barge et al., 2020).

Over the years, many studies have been conducted on the digitalization of meat supply chains that integrate the Internet of Things (IoT) devices with such technologies as blockchain. The retail company Walmart, together with IBM, implemented a blockchain solution, based on Hyperledger Fabric, to track and trace pork meat from the initial pig breeding phase to the final packed product in China. The proposed system involved the use of IoT devices, such as RFID tags for pig identification, cameras to monitor the slaughtering process, temperature and humidity sensors and GPS systems installed on transport trucks, and barcodes for the communication of certified data to the final consumers (Kamath, 2018). Rejeb (2018a), instead, proposed introducing blockchain to improve traceability and guarantee the product integrity along the Halal meat supply chain. The main aim of the author was to integrate blockchain with already existing systems based on the use of RFID tags, barcodes, and sensors in order to render them decentralized and more transparent.

From the analysis of the meat sector, it emerges that barcodes, RFID devices, and blockchain technology are the most frequently adopted anticounterfeiting solutions. Since a significant issue for this sector is the loss of traceability information during the slaughtering or sectioning process, future research should be focused on innovative methods to impede fraudulent actions during these supply chain steps. The fast and accurate control of data flows is crucial, and instruments based on Artificial Intelligence algorithms could be useful to improve the efficacy of such processes. Preliminary studies that have demonstrated the effectiveness of employing AI techniques to achieve this goal have already been conducted (Biglia et al., 2022); however, further investigations should be carried out on this approach.

Fish, seafood, and their products. The complexity of the fishing supply chain and the high value of seafood products contributed to the occurrence of frauds in this sector over the years. An analysis conducted by Lawrence et al. (2022) showed that the most common seafood fraud incidents pertain to species adulteration, in particular for the presence of illegal or unauthorized veterinary residues, chain of custody abuse (absent, improper, or fraudulent health marks or certificates), misrepresentation of expired products, mislabeling of brand or certification, illegal or unauthorized international trade, illegal processing, and undeclared product extension (e.g. underweighting, added ingredients, overglazing). Frauds in the seafood industry concern not only fresh fish but also frozen products as demonstrated by Peterson et al. (2021). The adoption of prevention and mitigation strategies is crucial for seafood supply chains to counteract fraudulent activities that highly threaten public health, industry economics, and even undermine marine conservation efforts (Lawrence et al., 2022).

The use of QR codes and RFID devices has become popular for traceability purposes in the seafood sector. Hsu et al. (2008) proposed an RFID-based traceability system for live fishes (supplied alive to restaurants and only cooked after the consumer choose the fish). The system involves the application of an HF RFID tag to each fish for identification purposes. The reading of the tag provides customers and consumers with detailed information about the farming and transporting processes of each single product. Kresna et al. (2017) instead proposed using RFID devices to improve the traceability systems of tuna supply chains in Indonesia, which are currently based on paper documents. The developed system exploits RFID tags, applied to fish or to plastic containers, to acquire data in real-time from the various processes and to link and trace all the supply chain actors at different stages and in diverse geographical areas. Xiao et al. (2017) developed a system that integrates a wireless sensor network (WSN) with QR codes for the real-time monitoring of aquatic products along the cold chain. According to Lewis and Boyle (2017), the "Gulf Wild" nonprofit organization adopts the use of sequentially numbered gill tags with QR codes to each caught fish. The difficult removal of the tag from the gill allows the movement of the product to be continuously monitored along the entire supply chain; the QR code enables customers to access identification data about the ship, the captain, etc., and the final consumers to discover detailed information (species, place and catching method, place of processing) about the product they are buying.

Digitalized supply chains adopting IoT and blockchain technology for traceability are beginning to spread even in the seafood sector. The coupling of blockchain with RFID tags and QR codes to trace tuna fish was studied in a pilot project carried out by the World Wide Fund for Nature (WWF) organization (WWF, 2018). Wang et al. (2022) have studied the integration of Blockchain, Attribute-based encryption (ABE), the Internet of Things, and Artificial Intelligence (AI) technologies (e.g. image processing and biosensing) to develop a system to prove the origin of fish for the real-time tracing of fishery products along the supply chain, and for the automatic objective evaluation of fish quality. Khan et al. (2022), instead, focused on crustaceans and developed a digital traceability system for the Bangladeshi shrimp supply chain. The proposed system allows users to manually register data in the blockchain through mobile/web applications and automatically using IoT devices. According to the authors, there are several advantages of adopting the blockchain technology in this sector, for example, it allows consumers to find out about the environmental sustainability and ethical implications of the chain or it can be used to contrast frauds by enabling the identification of shrimps of scarce quality that have been priced and mislabeled as premium products. According to Tsolakis et al. (2023), although the benefits of blockchain technology are well recognized by supply chain actors, there is still skepticism in adopting it due to the great technical complexity and the high associated costs. Therefore, future research should be focused on strategies to overcome these limitations and on the assessment of consumers' approach to digitalization. Moreover, as for the meat case study, innovative ICT technologies, such as AI or machine learning, should be further investigated to improve the control of data flows that is crucial to contrast the loss of traceability information often occurring during fishing activities and fish processing and sectioning.

Wine and spirits. Wine and alcoholic beverages, including vodka, rum, and whiskey, are often a target for fraud for several reasons, including their significant presence on the global market, their complex nature, and their high commercial value, which can lead to considerable profit margins. The adulteration of wine and spirits can occur at different point of the supply chain: it may concern the addition of unauthorized ingredients, the blending of different beverages, false declarations about the aging process, or even the mislabeling of the bottles.

Mislabeling is the most widespread fraud, as printed labels are prone to imitation, and advanced labeling technologies allow this kind of fraud to be prevented (Hellberg et al., 2021). Another very common type of counterfeiting for wines and spirits is the illicit refilling practice, which consists in the refilling of already labeled empty high-quality branded product bottles with lower-quality alcoholic beverages. This kind of activity is mainly carried out in restaurants and bars where the bottles remain open and may easily be refilled or mixed with cheaper brands of lesser quality, or even with water (Kuballa et al., 2018). In addition, according to Soon & Manning (2019), the trade of empty branded bottles is spreading globally. A gray market regarding empty bottles, some of which are sold online, generates very high returns (up to $350 per bottle).

Mechanical anticounterfeiting solutions, such as elements with tamper evident features, applied during the closures of the bottles can be used to prevent and contrast the practice of refilling. Currently, caps with a safety ring, mechanical and electronic seals, plastic and/or metal cap wrappers, shrinkable plastic films that cover the entire bottle or just the cap, and seals with holograms are being used. Antitopping caps that mechanically impede empty bottles from being refilled are also employed (Kutluğ et al., 2020).

In order to enhance the effectiveness of protecting high-quality DOC (Controlled Designation of Origin) and DOCG (Controlled and Guaranteed Designation of Origin) wines, the Italian Government has adopted a combination of different technologies, including mandatory official tamper-proof and authenticity warranty labels with advanced security printing technologies. In this case, a watermarked paper support containing multicolored fibers, which are visible under UV light or to the naked eye, is printed using fluorescent inks on a guilloche background. Microtexts are also printed on the seals. Moreover, item-level full traceability of each bottle is guaranteed by a unique serial code, which, in combination with an alphanumeric control code, allows the authenticity of the label to be verified. A bidimensional barcode (DataMatrix) is also present for the automatic reading of the information (IPZS, 2015). Digital technologies are gaining importance in the alcoholic beverages sector, and applications developed for smartphones can access supply chain traceability and product authentication information (Čakić et al., 2020).

Fine wines and liquors that bear holographic labels or seals can be found on the market. In Romania, the National Office of Vineyard and Wine Products (ONVPV) has introduced the mandatory use of security holograms on adhesive labels applied to the bottles of selected quality wines to certify their origin and authenticity. These holograms contain various security features, such as unique serial codes and QR codes, and they are ultra-destructible (Vacariu et al., 2018). Bidimensional barcodes have sometimes been replaced with advanced NFC technology in the high-quality alcoholic beverage sector. NFC tags are generally placed on the top of the cap of a bottle or over/under the label, or they are used in the form of electronic seals. An NFC tag has been located on the lid of a branded tequila (OTACA™) for protection purposes, and it is covered with a white coating. By scanning the tag, the customer can verify the authenticity of each single bottle, obtain information about the provenance and the place of distillation of the tequila, and even reorder the product (Identiv, 2022).

Popović et al. (2021) proposed a novel solution for the wine sector that exploits smart tags that consist of a QR code combined with prints with photochromic inks to digitalize single bottles of wine and to determine their authenticity. When scanning the QR code, the consumer also provides an update of the status and position of the bottle, which allows the bottle to be tracked throughout its entire lifecycle and any possible counterfeiting issue to be identified.

Del Mastio et al. (2016) exploited the digital watermarking technology to develop an innovative anticounterfeiting system for wine bottles. This system consists of an invisible unique digital watermark, which is inserted into the wine producer's logo image on the label. By taking a picture of the logo, consumers can be redirected to the wine information supplied by the producer and can verify the originality of the product. Čakić et al. (2020) proposed a system that is based on computer vision and optical character recognition (OCR) to read unique serial numbers reported on the labels of wine bottles.

Many authors have envisaged blockchain technology as a tool for the prevention of counterfeiting in the wine and spirit sector. For example, Biswas et al. (2017) proposed a system based on a private blockchain to track wine from the field to the bottle, in which the transactions of all the main subjects in the supply chain are registered. Singh et al. (2021) developed a blockchain-based solution for wine traceability that uses the One Time Password (OTP) authentication to verify the identity of the members of the supply chain and the authenticity of products.

Sun et al. (2019) designed a system, based on the combination of Ethereum blockchain and RFID devices applied to bottles to detect counterfeited liquors, which allows the transactions in the blockchain during the production, logistics, and selling phases to be automatically registered, thus guaranteeing data immutability. An interesting study on how the blockchain technology is currently adopted by five Italian wineries in different ways to combat counterfeiting was carried out by Danese et al. (2021).

The analysis of anticounterfeiting technologies used in the wine sector shows that a combination of several solutions is very often exploited to protect and authenticate products. Furthermore, it is evident that the wine industry is actively integrating the blockchain technology to enhance traceability. However, supply chain digitalization, based only on this technology, might not be so effective for anticounterfeiting purposes; future research should therefore be focused on the implementation of systems to digitize the supply chain in a more comprehensive and automated way. Although some studies have already explored the development of novel solutions that integrate cutting-edge digital technologies, including e-labels, the Internet of Things, the Cloud, and machine learning methods (Popović et al., 2021), additional investigations are still necessary in this field. Moreover, augmented and virtual reality-based solutions could be explored, due to their role in enhancing consumers' tasting experiences, which is becoming an increasingly important aspect (Spence, 2023).

Olive oil. Because of the uniqueness of its nutritional, sensory, and composition characteristics and its high economic value, olive oil is considered one of the foods most at risk to fraud (Casadei et al., 2021). The cost of frauds concerning olive oils since the year 2000 can be estimated in the region of several billions of dollars (Hellberg et al., 2021), and the most frequent scams in this sector include adulteration, addition, substitution, and falsified origin. All these types of fraud are closely related to mislabeling, with false declarations being reported on the labels (Casadei et al., 2021).

Consumers of olive oil are increasingly becoming attentive to the information reported on labels and especially to the details about the origin of the product. In the European Union, the country of origin of extra-virgin olive oil (EVOO) has had to be reported on the label since 2012 (EU, 2012). According to Bimbo et al. (2020), in spite of this law, consumers continue to distrust EVOO labeling because they suspect that such premium price products could be prone to fraud.

Among the available mechanical solutions, anticounterfeiting closures and seals are already widely adopted in the olive oil industry. Closures for olive oil bottles must guarantee hermeticity and must be provided with tamper-evident devices. The most common closures for glass bottles in this sector are screw caps and roll-on caps (Limbo et al., 2014). The adoption of nonrefillable containers (provided with antirefilling caps) for virgin olive oils served in the Ho.Re.Ca (HOtel, REstaurant, CAfè) sector has been mandatory in Italy since 2013 (Gazzetta Ufficiale della Repubblica italiana, 2014).

Advanced traceability systems to certify the origin of products are necessary to protect the high-quality reputation of EVOO. As in other sectors, there has been an increasing interest in digitalization and in the use of smartphones for authentication purposes in the olive oil industry. The adoption of such technologies as QR codes or RFID has been studied over the years.

The implementation of a traceability system that exploits RFID devices could be highly beneficial for olive oil companies in which the denomination of origin is mandatory, as suggested by Rejeb (2018b). The author, who claimed that the various analytical techniques available for the authentication of olive oils are not sufficient, proposed a theoretical framework for the traceability of olives in the postharvest phase, which is based on the application of RFID tags that store such information as the olive variety, the collection date, the olive growers, etc. to the crates of harvested olives. The main aims of the system are to prevent the entrance of nontraced olives into the supply chain, a better management of the lots, and assessment of the olive oil sources, all of which are important to indicate the origin of the product.

Conti (2017) proposed the adoption of the NFC technology within a tracking system to monitor all the stages of the EVOO supply chain. Similarly, Papaefthimiou et al. (2017) proposed using NFC devices for olive oil traceability and also for plant protection monitoring (chemicals, and fertilizer applications). The system, which was tested in a real case scenario in Greece, uses sensors for the acquisition of the quantitative and qualitative characteristics of olive oil during the oil extraction phase, thereby allowing certain olive oil quality attributes to be traced.

Abenavoli et al. (2016) proposed the use of QR codes containing data related to the outputs of different olive oil lots during each production phase. Data are registered by each supply chain actor in a software cloud-based solution. Guido et al. (2020) suggested the use of QR codes on EVOO bottle labels to allow the final consumers to autonomously find out about the history of a product, thereby increasing its perceived value. These codes summarize data about the olive growing, oil milling, laboratory analysis, etc. of each product that had previously been stored in a central database by all the supply chain operators.

As digital tracking is also spreading in the olive oil sector, Arena et al. proposed a blockchain-based system in 2019 that uses Hyperledger Fabric for the certification of EVOO. Fernandes et al. (2022) developed a platform, using blockchain and smart contracts that enables the immutable traceability of quality, and environmental and social sustainability indicators for all the stages of the olive oil supply chain.

Considering that the blockchain technology alone cannot guarantee the reliability of the recorded information, solutions that integrate blockchain with IoT devices for the automatic collection of data during the entire olive oil production process have been proposed (Alkhudary et al., 2022). Violino et al. (2020) developed an electronic traceability system for EVOO that involves integrating multiple technologies: RFID tags during the growing and harvesting phases, and QR codes during the subsequent stages. Moreover, QR codes, printed on the bottle labels of EVOO, are protected by a "scratch and win" system. Since the tracking solution was created using blockchain, when the consumers scratch the label and scan the QR code, they receive a digital token worth €0.05 in addition to the traceability-certified information.

Although some studies have already explored blockchain-IoT integration for EVOO supply chains, the research in this field is still at an early stage. According to Alsayat and Ahmadi (2023), such research should investigate the barriers to the implementation of IoT in olive oil companies, especially considering privacy and security issues. Moreover, future studies should be centered on methods to improve the automatic digitization of the entire sector, focusing on solutions that ensure the origin of olive oils to support mandatory certification labels. In such a scenario, big data analysis and AI models could be encouraging approaches. Indeed, apart from enabling faster and more accurate authentication of olive oils than conventional chemometric techniques, they also enable precise predictions to be made, for example, concerning their origin (Skiada et al., 2023). The use of AI and machine learning models in the context of the olive oil supply chain is in its infancy and deserves further investigation.

Concluding remarks

Food fraud is a global concern as it poses serious risks to both human health and the economy. From the analysis that we have carried out, it emerges that the solutions and technologies available to prevent and contrast frauds are numerous and heterogenous. Most of these technologies are already widely adopted in the automotive, pharmaceutical, IT, textile and clothing sectors, etc. Over the years, many studies have been conducted to assess the applicability of some of the anticounterfeiting solutions to food products. However, only a few of these technologies are currently routinely adopted in the food sector.

The more complex the supply chains are, the more they are likely to be vulnerable to fraud actions, and it is not always easy to understand at which point of the supply chain it is necessary to intervene for prevention purposes. It is therefore important to involve all the supply chain actors, including the final consumers, in the anticounterfeiting strategy. Efficient track and trace systems should be implemented to monitor the flow of materials and documents along the entire supply chain and to be able to promptly intervene in the case of the occurrence of fraud. The evolving digital context makes it easier to create robust, reliable, and shared traceability systems.

It should be noted that most of the systems proposed by the various authors in the literature imply the combination of several anticounterfeiting solutions. In fact, the integration of multiple physical and/or digital technologies leads to a higher level of product protection as fraudsters are hindered more in the perpetration of a fraudulent activity. However, it is also true that companies need to embrace the most practical and effective anticounterfeiting solutions, characterized by a maximum benefit/cost ratio. Such a consideration is important in relation to the average cost of the food product or food supply chain that has to be protected. Furthermore, since sustainability and environmental awareness are currently no longer an option, companies should carefully consider the sustainability level of the solutions they choose as not all the so far proposed solutions are aligned with environmentally friendly practices.

The attentive analysis of the four food industries affected the most by frauds has shown that barcodes, RFID devices, and track and trace systems (including blockchain) are the most widely adopted and extensively studied anticounterfeiting technologies. However, the more technology knowledge evolves, the more fraudsters become capable of replicating the existing anticounterfeiting solutions. It is therefore important to continuously develop new, more complex technologies to hinder their efforts.

Regarding physical solutions, the efforts have mainly been toward the development of innovative and sophisticated anticounterfeiting inks and materials that are difficult to produce and therefore to be forged. Additionally, the development of new security labels generated using nondeterministic processes is of great importance as well as the creation of new systems to conceal labels which only ensure readability under particular lighting conditions/reading angles.

As far as digital technologies are concerned, since their use can be complex, because they involve numerous supply chain actors, the assessment of their adoption is strictly related to the degree of digitalization within the enterprises, the presence of secure and updated centralized databases, which can be mandatory or voluntarily adopted, the awareness of consumers about traceability, and their ability to use identification codes and devices (e.g. apps and smartphones equipped with Bluetooth, NFC, QR code scanning). The standardization of electronic labeling and traceability adopting specific requirements and restrictions is therefore crucial to facilitate their implementation along the whole supply chain.

Since the availability of additional and detailed information has the potential of increasing the value of products, industries may be willing to invest in digital anticounterfeiting solutions to enhance their clients' fidelity and to protect their products, even at a premium cost. A subsequent major concern is whether consumers would be willing to purchase such products at higher prices. Moreover, concerns about using IT systems in agriculture and in the food sector arise because of the lack of IT skills and infrastructures in such fields, which could limit the collaboration of all the stakeholders.

Digital technologies can help in prevention strategies as they allow food fraud events to be predicted through advanced big data analysis methods, which can also hinder the on-line gray market. Furthermore, the implementation of advanced traceability systems, coupled with artificial intelligence algorithms, could be adopted in several supply chains that implement more complex anticounterfeiting methods that are based, for example, on machine learning techniques combined with image recognition.

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