Comprehensive REVIEWS in Food Science and Food Safety

Tackling Fraudsters with Global Strategies to Expose Fraud in the Food Chain

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Abstract: Deliberate adulteration of food products is as old as food processing and production systems. Food adulteration is occurring increasingly often today. With globalization and complex distribution systems, adulteration may have a far-reaching impact and even adverse consequences on well-being. The means of the international community to confront and solve food fraud today are scattered and largely ineffective. A collective approach is needed to identify all stakeholders in the food supply chain, certify and qualify them, exclude those failing to meet applicable standards, and track food in a real time. This review provides some background into the drivers of fraudulent practices (economically motivated adulteration, food-industry perspectives, and consumers' perceptions of fraud) and discusses a wide range of the currently available technologies for detecting food adulteration followed by multivariate pattern recognition tools. Food chain integrity policies are discussed. Future directions in research, concerned not only with food adulterers but also with food safety and climate change, may be useful for researchers in developing interdisciplinary approaches to contemporary problems.

Keywords: food chain integrity, food fingerprinting, food fraud, forensic chemistry, fraudulent ingredients

Introduction

Food fraud is committed with the intention of deceiving consumers (Ryan, 2016). Although it can occur for a variety of reasons, fraud is often driven by a desire to derive financial profit. The U.S. Food and Drug Administration (FDA) defines economically motivated adulteration (EMA) as "the fraudulent, intentional substitution or addition of a substance in a food product in order to increase the apparent value of the product or reducing the cost of its production, that is, for economic gain" (Grundy et al., 2012; Spink & Moyer, 2011).

Food fraud frequently arises from the need to compete with other more powerful businesses, manufacturers, food service establishments, and major food retailers (Manning, Smith, & Soon, 2016). The Halal meat scandal (Smith, 2004), the Eurovet scandal (Smith, 2013), and the black fish scandal (Smith, 2015) are only a few examples of high-profile food fraud. The large profits obtained by fraud in the food supply chain may be comparable to those of cocaine trafficking but involves lesser risks (Manning et al., 2016). On the other hand, food safety and quality issues are unintentional, even if they have an economic impact on a specific food or food ingredient industry in the form of reduced purchases, brand equity, product recalls, or process controls (for example, Ahmadi, Ghassemzadeh, Sadeghi, Moghaddam, & Neshat, 2010; Hussain & Dawson, 2013).

Occasionally, the driving force for fraud is a shortage of a given food component. For instance, the horsemeat scandal was in part motivated by a reduced European supply of beef and other meat products. Other reasons for the increasing food adulteration may be the growing complexity of the current global food supply system, the expansion of world trade across novel markets, and the steady rise in food prices (Huck, Pezzei, & Huck-Pezzei, 2016). Global trade has increased the distance food must travel from its production site to consumers (Aung & Chang, 2014). Thus, many product ingredients and inputs are now sourced from a wide range of countries. It is difficult to trace the source of unintentional contamination and related food safety concerns (Riviere et al., 2012). However, it is often more difficult to detect instances of intentional product fraud, especially in highly processed foods with multiple ingredients and inputs from multiple suppliers (Riviere et al., 2012).

Trends in food production and changes in production systems have compounded with globalization of food supply to make the ultimate supply chain much more complex (Quested, Cook, Gorris, & Cole, 2010). Globalization and trade liberalization have increased the risk of food safety policies such as the development and implementation of food safety standards becoming ineffective, which might have deleterious consequences on health and further increase the growing threat of foodborne diseases worldwide (Manning & Smith, 2015).

Because the primary motivation for fraud is illicit monetary gain, the particular type of food that may be or become adulterated is of secondary importance. It is in fact the opportunity of committing

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doi: 10.1111/1541-4337.12419

fraud that generally triggers fraudulent behavior (Centers for Disease Control and Prevention (CDC), 2003; Gossner et al., 2009; Johnson, 2014).

The many kinds of food fraud classified by Georgiou and Danezis (2017) are of either of these two main types (Table 1):

1. Selling food that is unfit and potentially harmful by, for example,
   a. Recycling animal byproducts back into the food chain;
   b. Packaging and selling food products of unknown origin; or
   c. Selling goods that are past their "use by" date.
2. Deliberately misdescribing food by, for example,
   a. Adulteration in the form of replacement of a high-value product with a cheaper alternative (for example, selling farmed salmon as wild); or
   b. Making false statements about the source of food ingredients (for example, their geographic, plant, or animal origin).

Available food fraud databases contain no entries for dietary supplements (Cole & Fetrow, 2003). Therefore, further research in this area is needed to meet the fast growth of the nutraceuticals market. Assessing food products and categories in terms of appeal to fraudsters (Daly & Gee, 2016) may facilitate more efficient interventions based on (a) more frequent forensic quality inspections or auditing, (b) shifting audit focus to fraud, and (c) developing more effective security measures to avoid or reduce insertion of fraudulent replacements into the supply chain.

Even when food fraud is not causing significant adverse health effects to consumers, it has a detrimental effect in food supply chain. For example, adulteration may cause consumers, regulators, industry, and trading partners to mistrust the food supply chain, and eventually lead to market and trade disruptions (Spink et al., 2016). Current food safety tools might be useless in the case of food fraud not causing a significant food safety risk. Available tools appear not a significant deterrent to food fraudsters. As a consequence, many traditional food risk assessment tools are holistically useless to predict food fraud incidents (Kearney, 2010).

This review provides some background into the drivers of fraudulent practices (EMA, food-industry perspectives, and consumers' perceptions of fraud) and discusses a wide range of the currently available technologies for detecting food adulteration followed by multivariate pattern recognition tools. Food chain integrity policies are also discussed. Future directions in research, concerned not only with food adulterers but also with food safety and climate change, may be useful for researchers in developing interdisciplinary approaches to contemporary problems.

Major Food Fraud Alerts

Most existing food labeling systems cannot guarantee food quality or safety (Aung & Chang, 2014)—nor, obviously, food authenticity. Extrinsic factors such as price, geographic origin, production methods, health and safety claims, and environmental welfare standards are often used as "value descriptors" instead of intrinsic properties of foods. So-described products are thus susceptible to EMA including mislabeling (Bigot, Meile, Kapitan, & Montet, 2015; Manning, 2016; Müller & Gaus, 2015), which may detract from food authenticity and deface the reliability of the producing brand or producing country as a result.

Counterfeit foods are closely similar to legitimate products in packaging color and materials, and labeling design and trademark, and are sold on the same markets as the originals. In this situation, detecting adulterants is often rather challenging. Misrepresentation has been found to occur in different steps of the food marketing process and also in different forms (Meloni, Arca, & Piras, 2015). Thus, some counterfeit products fail to specify some flavorings or additives they contain; also, the country of origin may be inaccurately specified to attract consumer loyalty, not only for the present, but also in the long term. Clear, reliable labeling of allergens is needed to improve quality and safety in healthcare products; therefore, failing to report allergens can also be considered mislabeling. More importantly, it can cause a range of adverse health effects and at times has caused fatalities, for example, two people died due to anaphylactic shock after eating products from a mainstream retailer "Pret a Manger" in U.K. (House of Commons Official report, 2018).

According to a systematic literature review and the information from food fraud databases (Čížková, Voldřich, & Pipek, 2009; NSF International, 2014), food frauds typically take the form of false statements, such as the following:

a. False geographic origin, species, or varieties (for example, substituting common wheat for durum wheat; labeling Greek or Turkish olive oil as Italian or Spanish; replacing botanically derived natural vanillin with synthetic vanillin).
b. False origin to reduce importation costs (for example, labeling a non-EU product as EU-produced).
c. False production processes (for example, food falsely labeled as organically produced; nonvirgin olive oil marketed as virgin).

Consumers should always suspect usually expensive products sold at low prices (Hoyer, Pieters, & MacInnis, 2013). Labels that are crooked or poorly printed, or contain spelling errors, should trigger an alarm. Similarly, packaging irregularities such as missing wrap-around seals on bottles are a key sign, and so is the absence of a label or the presence of one that can be easily removed.

Research has revealed that liquid and ground foods are easier to manipulate and hence more commonly adulterated (Bellatti, 2016; Breathnach, 2016), especially if the adulterant is widely available and adulteration merely requires dilution or mixing. Table 2 shows major instances of food fraud as classified into leading food categories and their potential risks on health. For example, when buying virgin olive oil, it is key to seek labels that indicate the place of origin. As regards to ground materials, instant coffee can be easily adultered with powdered ingredients. In the same way, costly spices like saffron can be easily adultered with tainted onion. Therefore, saffron should be acquired in whole threads, which are much tougher to fake.

Food-Industry Perspectives on Fraud

Based on a literature review (Bindt, 2016), it can be concluded that food fraud causes sales drops between 13% and 80%, and stock prices decreased between 37% and 75%. In relation to the price of an adulterated product, the price was 1.5 to 4 times higher than the genuine product. In addition, confidence is affected by food fraud. Decreases in trust in industries ranged between 7% and 64%. Concerning the amount of multinationals involved in recalls, the amount of multinational companies ranged between 5 and 22. According to the Global Food Safety Initiative (GFSI, 2014), industry is expected to work toward mitigating the risk of food fraud. Organizations, such as Nestlé (2016), have developed their own vulnerability assessments and appropriate control plans. Assessment, which can be applied to targets from animal

Table 1–Common types of food fraud.

Replacement	Examples	References
Dilution of an authentic ingredient with an adulterant or a mixture of adulterants.	Manipulation to increase milk apparent protein content Increase lemon juice titratable acidity with citric acid. Extra water in frozen fish. Nondeclarations and false claims	Gossner et al. (2009), Penniston, Nakada, Holmes, and Assimos (2008), Cardin (2009), Downey (2016)
Addition	**Examples**	**References**
Addition of a nonauthentic substance to mask a lower-quality ingredient.	Use of color additives in poor-quality paprika.	Albala (2015)
Removal	**Examples**	**References**
Omission of a valuable constituent without the purchasers' knowledge.	Removal of nonpolar constituents (fat and flavors) from paprika.	Pruthi (1999), Arvanitoyannis (2016)

Table 2–Leading food categories with reported cases of food fraud in alphabetical order (NCFPD, 2013).

Food item	Frauds type	Potential risks	References
Clouding agents	Food processing aids for enhancing the appeal of a food component are used when not authorized.	Plasticizer di(2-ethylhexyl) phthalate (DEHP) is associated with cancer and reproductive disorders.	(Sreenath, Crandall, & Baker, 1995)
Coffee and tea	Ground coffee may be cut with other ground and roasted plant materials. Anyway, instant coffee may be easily imitated.	Tea can contain leaves from other plants, and colored saw dust.	(Jumhawan et al., 2013)
Culinary spices	Ground black pepper, vanilla extract, turmeric, star anise, paprika, and chili powder are spices prone to fraud.	Dyes have been used to color paprika, chili powders, and curries, but some have been banned for foods.	(Black, Haughey, Chevallier, Galvin-King, & Elliott, 2016)
Fruit juice	Juices may be diluted with water or adultered with a cheaper juice. In some cases, juices may be only water, dye, sugar, and flavors.	Deteriorated product or potential contamination.	(Penniston et al., 2008)
Honey and natural sweeteners	Honey and other natural sweeteners may contain added sugar syrup. Geographic origin is also a frequent motivation for fraud.	Honey might contain pesticides or other pollutants such as heavy metals.	(Arvanitoyannis, 2016)
Milk and dairy products	Milk from cows adultered with other types of milk, or been adulterated with components such as melamine. Infant formula can be affected.	Melamine is known to pose a public health threat.	(Handford, Campbell, & Elliott, 2016)
Olive oil	Olive oil can be adulterated with a lower-cost substitute, such as olive oil from a different origin or any other type of oil.	Nut or legume oils pose a problem for consumers with allergy.	(Pérez-Jiménez, Besnard, Dorado, Hernandez, & Bakkali, 2013)
Organic food	Products fraudulently labeled as organic have been detected for food ingredients.	Assurance standards on food safety are not guaranteed.	(Hohmann et al., 2014)
Seafood	Higher-value seafood can be substituted by more affordable species at stores, restaurants, and so on. Some substitutions are used to evade importation taxes.	Some substitutions have been associated with fish poisoning or allergens.	(Leschin-Hoar, 2011)

Table 3–Difficulty metrics and criteria for food adulteration and substitution.

Difficulty	Physical state	Availability of adulterants/substitutes	Ease of adulter-ation/substitution	Labeling/Tamper proofing
5 (High)	Whole	Restricted/Technically complex	Complex processing	Retail pack
4	Heterogeneous/Solid chilled	Expensive	Repackaging	Barcode
3	Solid/Frozen	Available at a cost	Freezing	Integral/Tamper-proof
2	Powder	Widely available	Labeling	Sticker/Removable
1 (Low)	Liquid	Freely	Dilution/Mixing	Bulk/None

feed and primary production to manufacturing and catering, allows vulnerabilities in the food supply chain to be identified. A company's vulnerability to food fraud is determined by three main factors: opportunities, motivations, and absence of control measures. Opportunities and motivations arise from the company's internal and external environment (SSAFE, 2015). The potential risk derived from these two elements can be improved by a third element: fraud control measures for detecting or preventing fraud. Table 3 lists selected factors that hinder food adulteration. In this way, FoodDrinkEurope (2016) recommends its members to consider the following building blocks for their food fraud mitigation procedures and action plans:

1. Develop a food fraud risk management system incorporated within companies' food safety/quality management systems.

2. Conduct Food Fraud Vulnerability Assessments: collect and evaluate internal and external information at appropriate points along the supply chain (including raw material, ingredients, products and packaging, supplier information) to identify vulnerabilities to food fraud.
3. Develop Food Fraud Prevention Processes, along with practical guidance (for example, a food fraud prevention tool box including, for example, analytical tools).

The U.S. Pharmacopeial Convention (USP, 2017) defines a food fraud management system as a continuous process that starts with an assessment step intended to recognize food fraud vulnerabilities, and is followed by the design and evaluation of an elimination approach. In response to changes that may affect the previously identified weaknesses (for example, a new adulterants; variations in the food chain), the complete procedure must be repeated to guarantee continuous efficiency. The European Parliamentary Research Service (EPRS, 2014) has developed a general strategy for avoiding food fraud that can consists of the following steps:

- Evaluating weaknesses according to SSAFE (2015), which requires knowing
    - Materials and risks (sustainability factors, origins, new potential issues);
    - Suppliers (company, registry);
    - Supply chain (complexity, provisions, accessibility); and
    - Existing control procedures.
- Designing new mitigation approaches and conducting antifraud measures (Elliott, 2016).
- Validating applied measures (Elliott, 2013).

Identifying the susceptibility of an ingredient to fraud (Curll, 2015) entails assessing the following points:

1. Weakness due to issues intrinsic to the food component (Cavin et al., 2016): The ingredient price and its history, composition, and level of processing are independent of the actions taken by the customer. Some ingredients are especially susceptible to adulteration (for example grounded spices).
2. Weakness due to issues influencing the business: The need for a particular ingredient, market price fluctuations, and global demand may increase this vulnerability. Rises in price and limited supplies of a particular ingredient due to climatic adverse conditions (Shiferaw et al., 2014) or the action of a new pest are examples of this kind of situation.
3. Weakness due to issues under the buyer's control: This refers to the efficiency of a company's antifraud policy as regards to traceability, quality specifications, and robustness of applied control programs, for example.

Briefly, evaluating the risk of fraud necessitates knowing the intrinsic susceptibilities of the ingredients, the weaknesses of the business, and efficient controls in order to diminish the risk of food adulteration. It should be noted that weakness evaluation is a continuous process (Richards, Melancon, & Rately, 2008) that should be sustained with new data in response to circumstances.

Ensuring suitability in raw material qualifications is a good preventive measure against food fraud (Cavin et al., 2016). For instance, detailing the UV characteristics of extra virgin olive oil can help highlight adulteration with others oils. Particular properties to be monitored should be measured with suitable analytical methods that consider the singularities of the studied ingredients.

When the fraud risks have been recognized and a set of analytical control criteria defined, the National Research Council (NRC, 2003) recommends establishing a control plan. A control plan allows a company to build trust on its dealers and confirm that the mitigation actions are working properly. Raw materials should be monitored by using appropriate analytical tools to prove authenticity. Such methods should be selective, specific, and adequately sensitive to verify that the authentication procedure is proficient. There are two different methodologies to these verifications, namely:

- Targeted analyses for parameters included in the specifications of the material; and
- Untargeted analyses on the integrity of the raw material.

Targeted analyses may be additionally conducted by authorities at particular raw material processing sites (FDA, 2005). It is critical to keep updated with related publications as they can provide an early warning of fraud trends and new threats, or suggest reprioritization of existing threats (for example, climate impact on certain crop yields and subsequent fraud in response).

Thus, it is of utmost importance to generate a rapid alert when a fraudulent product is detected (for example, reporting the case to the competent local authorities and national food crime units for further investigation). Horizon scanning can be a useful tool for analyzing threats and opportunities emerging in the medium to long term (Alba, 2017). For example, climate change is likely to reduce coffee production—and raise prices and boost fraudulent activity as a result.

Consumers' Perception of Fraud

Consumers make their purchases on the basis of "quality attributes" (Grolleau & Caswell, 2006) such as provenance, production (GMOs, organic, free-range), ethical issues (animal welfare, fair trade), and sustainability (food miles). Consumers have a right to expect that the foods they consume are safe and of a high quality (Consumer Voice, 2016). Although consumers, governments, and other stakeholders also have an important role, the food industry bears the ultimate responsibility for developing and implementing proper controls to guarantee that their products will fulfill consumers' expectations of safety and quality (Harris, Brownell, & Bargh, 2009). The immaturity of ingredient testing, the dependence on whistle blowing, and the fragmentation of food supply chain, which moreover is not high tech, makes easy violation of common food standards with good financial gains, and consequently exposed us to food fraud (Rasco, 2014). Until very recently, the priority was on food safety over food fraud. This coupled to our paper and pencil approach in the 21st century has created the information asymmetry that clearly benefits food fraudsters for covering their tracks.

Consumers expect that their well-being holds a high value, and is supported by a system that will oversee food crises (Giovannucci et al., 2012). Consumers may experience financial, psychological, or health losses. The problem is information asymmetry; thus, producers and sellers are usually better informed about food safety and quality attributes than are buyers and consumers, and this asymmetry has serious implications on consumers' trust (Table 4). Consumers should look for authenticity cues allowing them to rest assured that a product is genuine or of the expected quality (Liao & Ma, 2009). Authenticity can be safely checked in various ways, namely:

Table 4–Consumer implications of food fraud.

Health	Emotional response	Discredit	Control
Intimately related to health (for example, nutritional quality)	Adulterated foods are unacceptable to consumers	It is socially unacceptable to give inauthentic gifts	Failure to decide about food authenticity
Anxiety due to unknown effects, mostly on child health	Feelings of fear, anger, and being cheated	The loss of "face" is an important negative impact	Perceived lack underpins the negative effects of finding food that is fraudulent
Concern about the safety of the overall food chain from farm to fork	Level of acceptance highly varies according to consumption situation	Unknown likelihood that they would encounter "fake" food	Lack of trust in the supply chain due to well-known food safety incidents including food fraud

1. Externally (with quality criteria certified by quality-protecting organizations).
2. Constructivistically (staged by entities such as companies as described in the "Food-Industry Perspectives on Fraud" section).
3. Existentially (by consumers with experience in distinguishing authentic from fraud).

Consumers are increasingly demanding more comprehensive information to choose food products; therefore, representation of a device for fraud detection on food markets is one of the most effective food safety approaches to have emerged in recent years. DNA-based tags are among the most useful methods for food certification used in food safety management systems (Machado-Schiaffino, Martinez, & Garcia-Vazquez, 2008). Genetic markers have been successfully used for species identification in recent years (Garcia-Vazquez et al., 2011). Other technologies based on the use of infrared light to monitor and control process quality have also been explored (Ellis, Muhamadali, Haughey, Elliott, & Goodacre, 2015). Molecular markers have been used to authenticate species in quality control methods for identifying mislabeling of commercial food products (Doosti, Ghasemi Dehkordi, & Rahimi, 2014; Teletchea, Maudet, & Hänni, 2005). Although a very large number of methods have been developed and successfully used for food authentication in recent years, no accurate enough commercially available method for consumers currently exists; rather, most control strategies have been specifically designed for industrial use (Charlebois, Schwab, Henn, & Huck, 2016; De La Fuente & Juárez, 2005).

Consumers perceive food fraud and adulteration to be inextricably linked to food safety and unknown implications for health (Paul, 2009). They tend to trust supply chains where they perceive regulation is especially rigorous. Instead of structural trust, they have high levels of kinship trust and seek reassurance from kinship networks prior to purchasing. In addition, they rely heavily on "indexical cues" to establish the authenticity of food products. They are entitled to expect that a recovery system be in place and that can be immediately enabled if needed.

Although some may think that food fraud is fundamentally an inoffensive act, it is actually damaging the whole food industry. According to Pricewaterhouse Coopers (PWC, 2015), food businesses require consumer trust to grow and offer high-quality products. Most food companies are ethically sound, but a few cases can be enough to damage the reputation of an entire industry. In addition, consumers with allergies or intolerances can be importantly affected by this kind of fraud. Therefore, food fraud is not only a socioeconomic problem, but also a public health issue. There is a need for public committees on food integrity to work with industry in detecting fraudulent cases. In addition, consumers should be actively involved and demand proper answers from the industry and authorities regarding antifraud policies and strategies.

Many companies and research centers are fostering the development of new technological systems for rapid verification of the information on the labels. For instance, smart sensors can be integrated into the label and the corresponding information (production, distribution, and so on) can be easily accessed by the consumer's smartphone. In the future, empowering consumers with these technologies will make them the most powerful supervisors of the food industry. According to the World Economic Forum (WEF, 2017), technology will help to root out food fraud; in the meantime, since the foods most easily adulterated are liquids, granulated foods, and inhomogeneous solids, we can give the following recommendations to consumers:

- Buy whole food whenever recognizing the species is possible.
- Buy fresh food from local producers.
- Reduce your dependence on processed foods.
- Limit purchases of foods requiring extensive label ingredient lists.
- Read labels.

Food Authentication Techniques

Analytical testing services underpinned by scientific expertise, a detailed knowledge of current and emerging regulations, and internationally recognized quality standards are of paramount importance with a view to protecting consumers from food fraud. No method is better than others are; all have their advantages and disadvantages; the most appropriate methods must be selected for each application. That is why, in this section, we describe the most commonly used methods, and their weaknesses and strengths, as well as anticipate other novel methods that are emerging with force. Table 5 illustrates the broad variety of techniques developed for this purpose and for screening the food chain for adulteration in recent times (Grundy et al., 2012). It remains difficult for consumers to detect fraudulent adulteration unless they know exactly what they are looking for. Fingerprinting techniques can be used to flag samples that are not authentic. However, they are only useful if an extensive database of authentic samples for comparison already exists. Some of the analytical techniques used to authenticate food include:

- Spectroscopies (MIR, NIR, Raman, NMR, UV–VIS).
- Separation techniques (GC, HPLC, electrophoresis).
- Mass spectrometries (MS, MS/MS).
- Stable isotope measurements (IRMS).
- DNA–PCR methods.

Measuring ratios of stable isotopes can be used for discriminating foodstuffs according to geographic origin or technological processes. In particular, determinations of the isotopic ratios of the light elements hydrogen (δ^2H), carbon (δ^{13}C), nitrogen (δ^{15}N), oxygen (δ^{18}O), and sulfur (δ^{34}S) in combination with those of heavy isotopes (δ^{87}Sr) and trace elements have allowed the origin of a number of food products to be established (Camin et al., 2010;

Table 5–Some cases and solutions for food authenticity testing obtained from a scientific literature survey.

(a) Identification of species/varieties

Food item	Specification	Technique	References
Fruits	Juices from oranges compared with mandarins	Dual-probe real-time PCR (qPCR) DNA-based analysis	Aldeguer et al. (2014)
Potatoes	Variety for different purposes: cooking, frying, puree, and so on.	DNA microsatellite analysis	Ashkenazi et al. (2001)
Meat speciation	Species changes and choices	Qualitative PCR over RFLP and quantitative real-time PCR	Calvo, Zaragoza, and Osta (2001), Lahiff et al. (2001)
Fish	Atlantic salmon compared with rainbow trout	Restriction Fragment Length Polymorphism (RFLP): Sequence-specific restriction enzymes digest the PCR amplicon and produce a species-specific pattern	Russell et al. (2000), Carrera et al. (2000)
	Yellowfin and Bluefin tuna compared with sardines	Single strand conformation polymorphism	Hold et al. (2001)
GMOs	EU demands labeling products with more than 1% transgenic material	Quantitative real-time PCR analysis	Pöpping (2001)
Pasta	The amount of nondurum wheat	Real-time PCR targets D-genome sequences present only in *T. aestivum*	Bryan, Dixon, Gale, and Wiseman (1998)
Apple	Identification/quantification of free and bound phenolic acids in peel and pulp of apples	high resolution mass spectrometry (HRMS)	Lee, Chan, and Mitchell (2017)
	Identification of apple variety	Dielectric Spectra and Chemometric Methods	Shang, Guo, and Nelson (2015)
	Identification of apples variety	Electronic nose and electronic tongue	Wu, Yue, and Yuan (2018)
Mung bean	Identification of mung bean variety	visible and near-infrared hyperspectral imaging	Xie and He (2018)

(b) Fraud and counterfeiting

Food item	Specification	Technique	References
Rice	Origin	SNIF-NMR	Verma, Khanna, and Singh (1999)
Wine and olive oil	Regions of origin	Site-specific Natural Isotope Fractionation-Nuclear Magnetic Resonance (SNIF-NMR)	(González, Remaud, Jamin, Naulet, and Martin (1999) Martin, Wood, and Martin (1996)
Offal	Offal in meat products	Primers designed to amplify only unmethylated sequences from internal organ-specific genes: phosphatidylcholine (liver-specific), copper amine oxidase (lung, kidney, heart, and spleen specific), and so on.	Al-Jowder, Defernez, Kemsley, and Wilson (1999)
Honey	Addition of dihydroxyacetone to clover honey followed by incubation resulted in methylglyoxal levels similar to those found in manuka honey	Methylglyoxal, dihydroxyacetone, D,L-glyceraldehyde and hydroxymethylfurfural were determined by HPLC	Adams, Manley-Harris, and Molan (2009)
Beef	Geographic origin	Combination of stable isotopes and multielement analysis	Zhao et al. (2013)
Tomatoes	Conventionally and organically grown	^{1}H-NMR profiling combined with PCA & LDA	Hohmann et al. (2014)
Milk	analysis of milk for the detection of adulteration, detection of goat, sheep, and cow milk in their mixture	Laser Induced Breakdown Spectroscopy (LIBS) combined with PCA	Moncayo, Manzoor, Rosales, Anzano, and Caceres (2017)
	rapidly detecting economically motivated adulteration (EMA) of milk	intact protein flow injection mass spectrometric fingerprints combined with PCA, PLS-DA, SVM	Du et al. (2018)
	detection and quantification of camel milk adulteration with goat milk	NIR spectroscopy with PCA, PLS-DA, and PLS	Mabood et al. (2017)
Tea & Coffee	detection of sibutramine adulteration in tea and coffee	ATR-FTIR spectroscopic method combined with PCA	Cebi, Yilmaz, and Sagdic (2017)
Almond powder	Detection and quantification of adulteration of almond powder samples with apricot kernel	Chromatographic fingerprinting with PCA-LDA and LS-SVM	Esteki, Farajmand, Kolahderazi, and Simal-Gandara (2017)
Peanut oil	Adulteration detection of peanut oil with soybean oil, rapeseed oil, or palm oil	Low-field nuclear magnetic resonance with PCA and LDA	Zhu, Wang, and Chen (2017)
Coconut water	Quantification of adulteration of fresh coconut water by dilution, and its masking with sugars	Raman spectroscopy with PCA	Richardson, Muhamadali, Ellis, and Goodacre (2019)
Butter	Detection of tallow adulteration in clarified butter samples	NIR spectroscopy with PLS-DA	Mabood et al. (2018)

(c) Traceability analysis

Food item	Specification	Technique	Reference
Cattle	BSE-free and traceability from farm to fork	With a combination of protein-based BSE-test and DNA-test (microsatellite analysis), the meat purchased by the end-consumer can still be traced back	Reed, Mendoza, and Beattie (2001)

(*Continued*)

Table 5–continued.

(c) Traceability analysis

Food item	Specification	Technique	Reference
Medicinal herbs	Safe recognition	Chemical fingerprints constructed by high performance liquid chromatography and converted into two-dimensional code	Cai et al. (2015)
Olive oils	Traceability, classifications, and so on.	Chromatographic profiles of several metabolite families and spectroscopic features followed by chemometrics	Messai, Farman, Sarraj-Laabidi, Hammami-Semmar, and Semmar (2016)
	Classification of Western Greek virgin olive oils according to geographical origin	Chromatographic analysis and LDA	Karabagias et al. (2013)
	Determination of geographical origin of organic olive oils	Calorimetric analysis with PCA	Mallamace et al. (2017)
Milk	Analysis of cattle tail hair in determining the geographical origin of raw cow milk	isotopic ratio analysis with PCA	Behkami, Zain, Gholami, and Bakirdere (2017)
Tea	Classification of Sri Lankan tea based on their region of origin	X-ray fluorescence analysis and PCA	Rajapaksha et al. (2017)
	Geographical origin traceability of tea	Multielement analysis with PCA	Li et al. (2018)
Honey	Traceability of honey origin based on volatiles pattern	Botanical traceability of unifloral honeys by chemometrics based on head-space gas chromatography with ANN-MLP	Cajka, Hajslova, Pudil, and Riddellova (2009)
Cucumber	Geographical traceability of sea cucumber	Near-infrared spectroscopy combined with chemometric	Guo et al. (2018)
Citrus	Traceability of argentine citrus	NMR and multivariate data analysis	Salazar, Pisano, González Sierra, & Furlan (2018)

Podio et al., 2013). However, these determinations usually require commodity-specific databases that are expensive to compile and maintain.

Mid- (MIR) and near-infrared (NIR) spectroscopy are among the most used spectroscopic techniques for authenticating food. Spectral signatures are obtained that may be considered to be "fingerprints" of the food (Bevilacqua, Bucci, Magrì, Magrì, & Marini, 2012; Pizarro, Rodríguez-Tecedor, Pérez-del-Notario, Esteban-Díez, & González-Sáiz, 2013). For example, Dhakal et al. (2016) successfully used Fourier Transform-Infrared (FT-IR) spectroscopy to detect adulteration in turmeric powder with Metanil Yellow (Figure 1).

Chromatographic methods, both gas chromatography (GC) and high-performance liquid chromatography (HPLC), afford high-resolution separation of compounds. They can be used in hyphenated techniques such as GC–MS, GC–MS/MS, LC–MS, and LC–MS/MS. Mass spectrometers are highly sensitive and universal, and can detect almost any organic compound of different classes and structures. Chromatographic profiles may be used as fingerprints of foods to control their quality and guarantee their authenticity (Gao et al., 2012).

Detecting specific nucleic acids in food allows one to determine the presence of particular ingredients in complex samples or to detect characteristic features of selected food constituents. DNA analysis has been used to meet needs such as GMO detection, microbial pathogen determination, or detection of undeclared allergenic components (Sforza et al., 2011). Polymerase chain reaction (PCR) allows trace amounts of degraded nucleic acids to be detected and their sequence established. These methods can be useful to identify meat or fish species and also genetically altered foods (Meyer & Candrian, 1996).

Different fingerprints are based on different physical and chemical principles (Zhang, Zhang, Dediu, & Victor, 2011). Therefore, each fingerprinting technique has its own intrinsic strengths and weaknesses:

1. In qualitative and quantitative terms, electrophoresis fingerprinting is a qualitative analysis technology that allows one to ascertain whether a given food component is present from differences in protein/DNA structure and electric charge. By contrast, spectral and chromatographic fingerprinting are better suited to quantitative analyses.
2. In relation to destructive or nondestructive nature, spectral fingerprinting is based on differences in element composition, and thus allows nondestructive detection. While this technique enables inspection in virtually real time, chromatographic fingerprinting typically necessitates several hours. However, electrophoretic and chromatographic fingerprinting are much more accurate than is spectral fingerprinting.
3. In terms of image processing, electrophoretic fingerprints are relatively simple and can be interpreted by the naked eye (under ultraviolet light). On the other hand, spectral and chromatographic fingerprints are so complex that they must be revealed by a computer and analyzed with powerful software.
4. In relation to cost and accuracy, chromatographic fingerprinting is especially expensive but provides the most accurate results. Electrophoretic and spectral fingerprinting are relatively more affordable but not so accurate.

Fingerprinting chromatography technology is suitable for food authentication in-house. When method transferability is needed for acceptance by authorities, producers, and consumers, food reference materials are necessary to normalize fingerprinting signals (Cuadros-Rodríguez, Ruiz-Samblás, Valverde-Som, Pérez-Castaño, & González-Casado, 2016). Compositional information on significant markers may be used to confirm authenticity and assure transferability for detecting food fraud.

There are other useful technologies for fraud detection (Ellis et al., 2012) including electronic noses and tongues, nanosensors, thin-film sensors, and nanoparticle detection systems. In this era of collaboration among the life, engineering, and physical sciences, novel developments will continue to tackle those negatively interfering with our food systems for whatever purpose.

A pan-European effort was conducted to develop generic procedures for food tracing and verification (http://www.cra.wallonie.be/en/the-projects/trace). The aim is to link key parameters of food with those of local environments. By studying climate and geology, scientists expect to be able to predict the

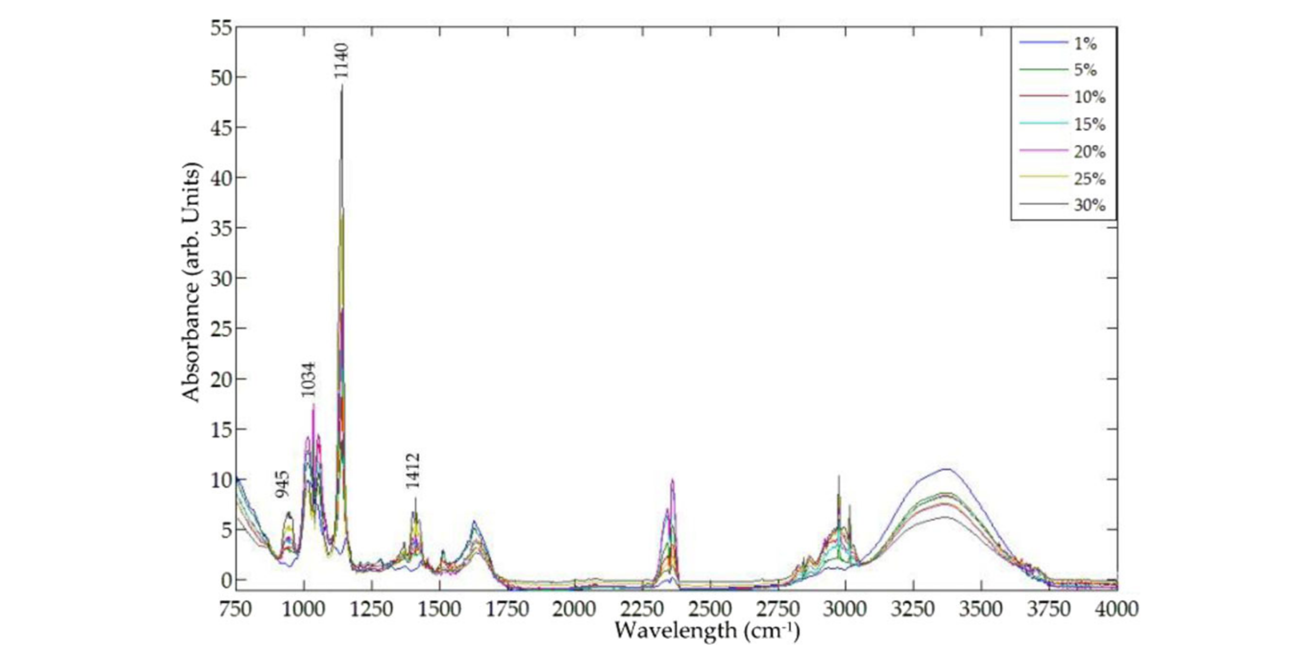

Figure 1–FT-IR spectra for turmeric powder (*Curcuma longa* L.) containing different amounts of Metanil Yellow as adulterant. Reproduced from Dhakal et al. (2016), licensed under CC BY-4.0.

parameter profiles to be expected from foods of a given provenance. It will then be relatively easy to check whether the actual profile of a food matches the predicted profile. Together with food mapping, spectroscopic and biological fingerprinting methods are expected to facilitate food verification. The increasing power of data acquisition and interpretation techniques has allowed atypical samples to be identified; also, it may facilitate the development of food verification systems affording a forensic approach to food authentication.

Multivariate Pattern Recognition Statistics

Data analysis has become a fundamental task in food fraud analysis, thanks to the large amount of information provided by modern analytical instruments. Below are described the foundations of the pattern recognition techniques most widely used for food authentication, with special emphasis on the practical requirements of the measured data, and on common misconceptions and potential errors (Berrueta, Alonso-Salces, & Héberger, 2007). Some cases and solutions for food authenticity testing obtained from a scientific literature survey are shown in Table 5 combining both fingerprinting techniques and multivariate pattern recognition tools.

A fingerprinting method uses the data contained in a highly specific feature or fingerprint (mass spectrum, IR spectrum, and so on) to understand the properties of the target system. Several statistical techniques can be used to reduce the dimensions of data, thus allowing significant information to be extracted from a complex data set. Such techniques allow revealing complex relationships among samples and detecting characteristic patterns that can be used to identify a certain group. This is the task of unsupervised pattern recognition techniques such as hierarchical cluster analysis (HCA), cluster analysis (CA), and principal component analysis (PCA) (Worley & Powers, 2013), which require no prior knowledge of the sample properties. PCA is the most used among these tools. A PCA model allows complex data to be projected into a lower-dimensional space by using orthogonal combinations of the variables, termed as "principal components" (PCs). Thus, PCs determine a reduced space to extract the most important information from the data. PCA also allows finding relationships in the data matrix by analyzing the structure of the observations and the variables (Hohmann, Christoph, Wachter, & Holzgrabe, 2014).

Multivariate methods can be also used to categorize a particular product or to quantify any of its properties. Based on the information previously acquired from a training set, classification models allow identifying to which category a new sample belongs. These models can be used, for instance, to authenticate organic products (Capuano, Boerrigter-Eenling, van der Veer, & van Ruth, 2013) or geographic origin (Wang & Yu, 2015). Supervised pattern recognition techniques including soft independent modeling of class analogy (SIMCA), k-nearest neighbors (kNN), partial least squares regression discriminant analysis (PLS-DA), linear discriminant analysis (LDA), support vector machine (SVM), and artificial neural networks (ANN) have been used in this context. Regression models establish a relationship between a quantitative sample parameter (the dependent variable) and multiple independent variables such as chromatographic peaks, absorption bands, and so on, which can be used to estimate the value of that parameter in a new sample. Different kinds of regression models can be used to detect fraudulent samples, including linear regression models using multivariate regression techniques such as principal component regression (PCR) and partial-least square regression (PLSR), together with nonlinear models based on SVM methodology and ANNs, have been used.

Essentially, the process by which a classification or regression model is constructed involves four steps, namely (Santos, 2014):

1. Building the sample set for training, that is to say, samples of known category for which the variables are also known.
2. Selecting significant variables for discrimination, what can be done by keeping those that contain relevant information for the classification.

3. Building the model from the selected variables on the training set and their known categories.
4. Validating the model with an independent set of samples (external validation) or samples in the training set (cross-validation).

Correct, tailored usage of proper chemometric tools to create regression and classification models requires special care to guarantee the following (Capuano & van Ruth, 2012):

- All categories represented so that all possible sources of variability are considered;
- Robust validation of the model (external validation is preferred); and
- Use of chemometric tools suited to the particular problem. For example, classification and regression trees, and quadratic discriminant analysis (QDA), remain unexplored in spite the good results they can offer.

A problem in this context is the absence of internationally accepted procedures for assessing methods based on fingerprinting techniques and classification models. Such protocols should state the performance characteristics to be checked and the specific criteria to be met in order to verify that a method complies with its expected performance characteristics.

Given the complexity of global pathways for the food supply chain, product fingerprinting in combination with chemometrics can be a useful tool for food fraud detection and control (Alewijn, van der Voet, & van Ruth, 2016). Consonni et al. (2016) to combat saffron mislabeling and adulteration with low-quality expired saffron material recently used this approach. They used an FT-IR database for authentic "fresh" and "nonfresh" samples (viz., samples stored for less than 4 or 7 to 12 years, respectively, after processing) to build a PLS-DA model that enabled successful classification of commercial samples of unknown history (Figure 2).

Food Chain Integrity Assurance Policies for Managing Fraud Risk

Because legislation on food labeling focuses on the protection of consumers' rights, it refers mainly to basic information such as ingredients (including additives), nutrition (including protein, carbohydrates, fat, and vitamins), origin, and safety (storage life, and preparation instructions). All with the hope that this information is controlled through appropriate randomized controlled trials in order to lower fraud risk.

Mol and Oosterveer (2015) consider four types of traceability systems: volume-based (mass balance), identity preservation-based (track and trace), separation-based, and certificate-based (book and claim), all with their own advantages and disadvantages. Current policies focus mainly on food integrity and the management of data and information rather than on the intrinsic nature of food products.

A holistic approach is needed when developing and implementing the management systems for food integrity (Table 6), and mitigating the problems when the systems fail. Ali, Tan, and Ismail (2017) studied non-Halal ingredients in a certified product and found that compliance with standards did not ensure food integrity. Safeguarding food integrity should be a concern for all stakeholders and the supply chain, since there are more opportunities for food fraud now due to the highly complex food system that has developed over the past 20 to 30 years. As there is no indication that it will get any simpler in the near to medium term, vigilance to food fraud should be increased following food chain integrity philosophy, which encompasses safety, quality, authenticity, and also traceability.

Many governments are requiring that food fraud hazards be assessed, and control plans be put in place to manage those hazards. Regardless of the current or future regulatory compliance requirements, to maintain a viable business, companies must reduce their fraud opportunity. Beyond the massive economic loss to industry by incidents, such as those of melamine or horsemeat, individuals are also being held criminally liable (Spink et al., 2016). The economic impact of food fraud is leading the industry to collaborate with academy in order to undertake a highly proactive approach for combating food fraud. Facing this sort of fraud is complex not only due to the lack of suitable analytical methods, but also due to the need of significant interdisciplinary work. Because there is usually no health hazard, the traditional detection and alert systems often do not detect food fraud that is economically motivated. Three types of public health risks can result from food fraud: Direct, Indirect, and Technical (Spink & Moyer, 2011). Direct food fraud risk occurs when there is an immediate or imminent risk to the consumer, such as the inclusion of an acutely toxic or lethal contaminant. Indirect food fraud risk occurs when the consumer is put at risk through long-term exposure, such as the build-up in the body of a chronically toxic contaminant through the ingestion of low doses. Indirect risk also includes the omission of beneficial ingredients, such as preservatives or vitamins. Technical food fraud risk is nonmaterial in nature. For example, food documentation fraud occurs when product content or country-of-origin information is deliberately misrepresented. The key actions with a view to reducing opportunities for fraud are to detect, deter, and prevent (Spink & Moyer, 2011; Spink, Moyer, Park, & Heinonen, 2013).

The surveillance effort needed to authenticate will be scientifically complex and challenging. Although detection is the most complex aspect, the top priority should be reducing opportunities for fraud (van Ruth, Huisman, & Luning, 2017). Once the specific human criminal acts and methods are understood, efficient and effective countermeasures and control systems can be defined. The role of food science and technology here will be in developing the specific methods needed to prevent fraud. In some cases, available technology may suffice; in others, authentication may pose enormous challenges that can only be met with effective control systems (European Parliament, 2016). The most important role for food science and technology here is to take a holistic approach to food fraud prevention. The risk of fraud is especially high when the probability of being caught is low and the potential economic gain high. The economic gain of fraud is further increased by a largely ineffective sanction regime; thus, sanctions are often relatively low and differ markedly among countries (de Lange, 2013). Available evidence that criminal organizations are increasingly involved in food fraud is very worrisome (FIA, 2018). In this sense, environmental criminology focuses on understanding and responding to the opportunity structures that make crime possible. Numerous opportunity-reducing techniques (for example, increasing the risk or effort of crime) may have the same potential for reducing food fraud (Spink & Moyer, 2011).

In addition to identifying the roles manufacturers, suppliers, consumers, and governments must play in reducing fraudulent activity, industry can improve its ability to detect fraud by adhering to three essential guidelines (Pimentel, 2014), namely:

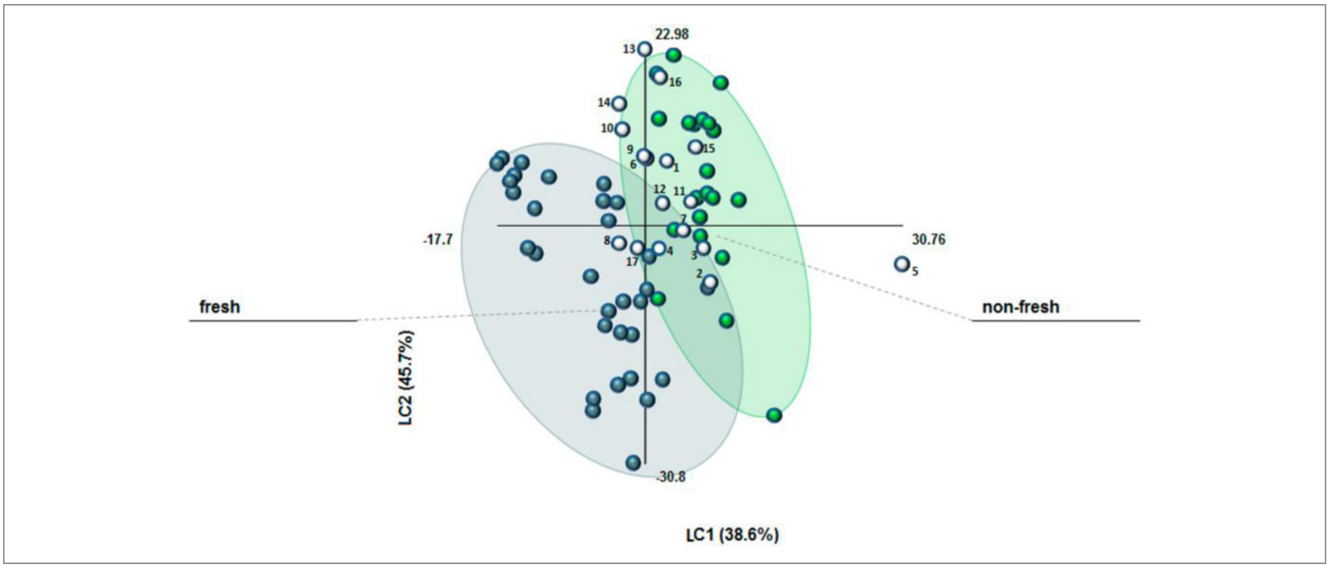

Figure 2–Scatter plot for the PLS–DA model as constructed from 52 authentic saffron (*Crocus sativus* L.) samples differing in geographic origin, harvest year, and storage conditions ("fresh": 0 to 4 years of storage; "nonfresh": 7 to 12 years of storage). Blue, green, and white dots represent "fresh," "nonfresh," and the 17 commercial samples of unknown storage history, respectively. Reproduced from Consonni et al. (2016), licensed under CC BY-4.0.

Table 6–Elements of food chain integrity (Bouzembrak & Marvin, 2016).

Element	Examples
Product integrity	Adulteration and economically motivated adulteration (EMA), counterfeit product, expiration date, simulation, tampering . . .
Process integrity	Diversion of products outside of intended markets, illegal importation, over-run, theft, and so on.
People integrity	Characterizations such as the cyber criminals and hacktivist, disgruntled individual, extortionist, extremist, irrational individual, opportunist, professional criminal . . .
Data integrity	Illegal importation, improper, fraudulent, missing or absent health certificates, improper, expired, fraudulent or missing common entry documents or import declarations, mislabeling, and so on.

1. By being more proactive in addressing economic adulteration. Although many companies have already implemented ways to counter global fraud threats, more needs to be done.
2. By finding new ways to share information and promote collaboration (for example, by identifying formal ways to collaborate with industry, government, academia, and NGOs, but also global engagement).
3. By engaging authorities as facilitators. Government authorities should setup international standards and share more information regarding potential fraud cases. This is key to address future threats before they become global.

Another possible solution is certification to global food safety standards (GFSI, 2011). Due to complex challenges in today's food supply chain, many of the world's largest food retailers are now mandating supplier certification to GFSI schemes. GFSI was established to ensure confidence in the delivery of safer food to consumers while continuing to improve food safety throughout the supply chain. These global standards address food, packaging, storage, and distribution for producers, manufacturers, and distributors. With exceptional technical expertise, calibrated auditors, and capacity for a timely path to certification, NSF International offers certification to GFSI-benchmarked standards as part of its comprehensive range of supply chain assurance services.

Although public health and food safety remain among the highest priorities, some authors have suggested that health and safety policies and controls should include food fraud (Pederson & Hernández, 2014). First, it is crucial to provide a clear, harmonized definition for food fraud if a nationally and internationally effective approach is to be developed. Then, existing food fraud detection mechanisms should be improved and available resources increased (for example, countries should cooperate more closely on cross-border investigations). Additionally, authorities should audit private control bodies and assume certain official control tasks. Rules regulating intermediary labeling should also be adapted to achieve a stricter control. The establishment of a legal obligation to report fraudulent activities in the food sector would be highly desirable. Finally, authorities should switch from an essentially administrative approach to a policing approach based mainly on risk profiling. Economical fines should be at least double the amount of the economic profit sought by the fraudsters.

Future Directions in Research on Food Fraud Exposure

The global food sector is facing significant challenges to ensure food safety, authenticity, and integrity of the global supply chain (FERA, 2016). Although the term "global supply chain" suggests being well connected, countries across the globe differ as regards food standards, customs, politics, or emergency preparedness (Abrams, 2015). Brand erosion, lost revenues, supplier mistrust, bankruptcy, lawsuits, product quality and safety recalls, and even death, are all real concerns of food fraud. Any of these events could stem from just one supplier, one raw food ingredient, one mislabel, or one questionable food shipment. As a result, today's stakeholders need to be more aware of actual and potential weaknesses in the supply chain to strengthen the weak links, and blockchain technology could come to the rescue (Galvez, Mejuto, & Simal-Gandara, 2018).

Although food fraud has been a matter of extensive research in recent years, relevant global quality research is still scarce (Spink et al., 2016). Food fraud has not been addressed holistically; also, it has been studied mainly in developed countries. In addition, the public and private sectors have failed in addressing policy and legal issues of the problem. Food fraud should therefore be a major research topic, especially in food imports, considering different viewpoints and multiple academic areas (Kendall et al., 2018).

The growing prevalence of food fraud, and adverse impacts on the global well-being and economy, necessitates advanced research in this field. The United Nations Food and Agriculture Organization and the World Health Organization (FAO & WHO, 2003) have identified some areas for improvement, namely:

1. Establishing a global food integrity system. Although countries can implement secure national systems, its integrity will be affected by external systems.
2. Developing effective models, theories, frameworks, methods, techniques, and tools for combating food fraud.
3. Investigating food fraud in developing countries, where many systems are operated manually.
4. Expanding research into the methods used by criminals to perpetrate food fraud with empirical studies aimed at filling existing gaps in knowledge.
5. Thoroughly investigating the national and global economic implications of food fraud.
6. Developing effective policies and legal frameworks to deal with food fraud and addressing consumers' concerns.
7. Identifying the roles of organizations, bodies, and individuals associated to fraud mafias to find their criminal challenges.

In addition, societal challenges in this area should be closely related to the food chain integrity (Holm, Nielsen, & Petersen, 2015):

- Meeting food demands for an increasing world population, not only by increasing food production, but also by reducing postharvest spoilage.
- Improving knowledge on special foods for special needs in order to meet unexpected hazards or fraud.
- Ensuring that, as socially expected, food is unspoiled and safe (that is, free of chemical contaminants, pathogens, toxic substances, and unexpected ingredients) by sustainably investing on innovative food science and technology to ensure safety in the whole food supply chain across the world.
- Assuring safety in convenient, ready-to-eat food for an increasingly urban population.
- Educating consumers in the risks of in-home preparation of foods, the root of many foodborne diseases.

The EU considers food fraud to be a serious issue and, for such a reason, it has recently funded the following Euro food integrity project (https://secure.fera.defra.gov.uk/foodintegrity/index.cfm). The project consortia consists of 60 partners from 18 EU countries, one from Argentina, and one from China, with the common aim of developing different tools to face food fraud issues. The project pursues not only to improve early detection capabilities, but also to develop methods, systems, and processes that will guarantee safety, quality, and authenticity throughout the food chain (The British Standards Institution, 2014). By doing so, consumers' trust of food authenticity will be enhanced and fraudulent products on the market will be more easily detected. By being more transparent about the methods that are currently being used in food authentication, food producers and food suppliers can prove to the public that their products are what they claim to be. With the knowledge that early-detection mechanisms are in place, consumers will be free to shop with the confidence that their food is authentic and safe, and the assurance that their health and well-being is protected (Sharma, 2017).

In Europe, food fraud is considered as a "top-5 Europe-wide focus." This is unsurprising since, according to the Commission of the European Communities, a sizeable portion of the European Union's food consists of value-added products (CEC, 2009). The European Union has tackled food integrity assurance by establishing the EU-wide Rapid Alert System for Food and Feed (RASFF), which monitors both adulteration and fraud, whether intentional or unintentional.

Authors' Contributions

All authors designed and contributed to all the sections in the review, although each of them concentrated their efforts in several sections: M. Esteki (Sections: Introduction, Major Food Fraud Alerts, and Multivariate Pattern Recognition Statistics); J. Regueiro (Sections: Food-Industry Perspectives on Fraud, Consumers. Perception of Fraud, and Food Authentication Techniques); and J. Simal-Gándara (Sections: Food Authentication Techniques, Multivariate Pattern Recognition Statistics, Food Chain Integrity Assurance Policies for Managing Fraud Risk and Future Directions in Research on Food Fraud Exposure).

Conflicts of Interest and Funding

The authors declare no conflicts of interest and no funding for this review.

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