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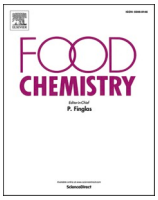

Overview of industrial food fraud and authentication through chromatography technique and its impact on public health

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ABSTRACT

Food fraud is widespread nowadays in the food products supply chain, from raw materials processing to the final product and during storage and transport. The most frequent fraud is practiced in staple food commodities like cereals. Their origin, variety, genotype, and bioactive compounds are altered to deceive consumers. Similarly, in various food sectors like beverage, baking, and confectionary, items like melamine, flour improver, and food colors are used in the market to temple consumers. To tackle food fraud and authentication, non-destructive techniques are being used. These techniques have limitations like lack of standardization, interference from multiple absorbing species, ambiguous results, and time-consuming to perform, depending on the type, size, and location of the system proved difficult to quantify the samples of adulteration. Chromatography has been introduced as an effective technique. It serves to safeguard public health due to its detection capabilities. Chromatography proved a crucial tool against fraudulent practices to preserve consumer trust.

1. Introduction

Food fraud is a common practice across the globe to attain economic gain by deceiving consumers, it may be in the form of causing adulteration in substance, tempering, diversion and grey marketing of ingredients, theft, misbranding, and stimulation in product quality (Spink et al., 2016). It is a major issue that compromises product reputation in the market. Food fraud has been reported in various food products, including meat and meat products (27.7%), cereal and bakery products (8.3%), milk and milk products (10.5%), and fish and fish products (7.7%) (Marvin et al., 2022). In major food sectors, most of the fraud was reported due to the expiration of date (58.3%), tampering (22.2%), and mislabeling of the country of origin (11.4%) (Marvin et al., 2022). Food fraud also occurs at the commercial level, which is typically deception or the provision of incomplete and misleading information, leading to a degradation in the quality of the product. The key features defining such fraudulent activities include failing to comply with food regulations (Glišić et al., 2023; Kazmi et al., 2023; Neo et al., 2022).

Food fraud is mostly considered a "food safety-related issue" so these two terms are interlinked. It compromises the food safety of the products which helps to secure food from unintentional harm. The food industry is advancing day by day, and consumer concerns about food safety issues are rising (Spink, Bedard, et al., 2019). Generally, food manufacturers and producers mainly focus on quality and adulteration of raw materials, neglecting hazards during processing but the origin of food, product category, and price of food are of great importance in predicting possible food fraud (Ali et al., 2023; Wisniewski & Buschulte, 2019). Hence, it is necessary to ensure that no physical, chemical, or microbial contamination causes harm or illness to the human body. Food safety is an integral part of community health, and now consumers are paying attention to it through awareness from different social media platforms (Moradi et al., 2020).

In this regard, the International Food Safety Authorities Network surveyed its 166 member countries. Almost 70% of the survey responses were based on food fraud incidents, where respondents were misled and tempered, which led to public health food safety hazards (Spink, Embarek, et al., 2019). A similar survey was conducted in Finland to detect food fraud, where 17 Finnish food control officers were interviewed, who revealed that 43.4% of food fraud cases occurred in the past five years (Joenperä & Lundén, 2023). Similarly, other countries

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like Brazil experienced a significant probe into major food corporations, particularly those in the meat industry, for engaging in bribery of inspectors, leading to corruption in food manufacturing processes. This misconduct resulted in tainted meals being served in public schools and the exportation of meals contaminated with Salmonella to Europe and Vietnam, consumers judge food on its origin and store reputation (Le et al., 2020). With the increasing demand for food control in the supply chain, consumers' demand for more monitoring in the supply chain increases (Owolabi & Olayinka, 2021). The rise in food adulteration scandals is often driven by economic incentives (Granato et al., 2018; Petković et al., 2022; Soon & Abdul Wahab, 2022). These factors may lead to food fraud vulnerability including factors that may lead to weakness of the system providing the chance of fraud (Yang et al., 2020). It varies throughout the food supply chain, ranging between food drivers and enablers and in areas lacking vulnerability assessment. From the consumer standpoint, examining food fraud is best approached by considering perceptions and attitudes concerning food safety, attitudes regarding food authenticity, and trust in institutions and experts. Consumers are on the front line facing food fraud, and Chinese consumers have adopted strategies to tackle this issue by purchasing directly from farmers rather than incorporating food into the supply chain, checking the packaging of food, and growing food for themselves to avoid fraud (Soon & Liu, 2020). Victims of food fraud provide the best information about the authenticity of food and it helps to reduce concern about food fraud (Charlebois et al., 2017).

At the commercial level, these food safety-related issues can be monitored through traditional practices by adopting good manufacturing practices, good agricultural practices, good hygiene practices, and through hazard analysis critical control points by identifying critical control points (Spink & Moyer, 2011). In this regard, food authentication confirms product analysis with its labeling description. It ensures the identification of facts that capture fraudulent acts (Danezis et al., 2016). The complexity of determining food authenticity requires evaluating various attributes, such as chemical, physical, biochemical, and microbiological properties (Oliveri & Simonetti, 2016). It is important to protect consumers, producers, and sellers from food fraud. Common inquiries in food authenticity often revolve around verifying the origin or composition of products. These queries pose significant challenges in verification without the aid of analytical fingerprints and authentic reference samples. Therefore, many techniques have been developed, which help in food authentication and food fraud detection. Different non-destructive methods have disadvantages not applicable to larger structures, are difficult to interpret expensive equipment, have small flaws that are difficult to detect in samples, and are not suitable for analysis (Borgwardt & Wells, 2017; Dwivedi et al., 2018). These are limited to an adulterant in a single matrix which is why advances in analytical methods seem to be the fitting way to avoid food fraud (Hussain et al., 2019).

In general, there are many non-destruction techniques used in food industries for the identification of un-acceptable material/foreign material in food and food products, such as Raman Spectroscopy, near-infrared spectroscopy, surfaced enhanced Raman spectroscopy, nuclear magnetic resonance Spectroscopy, ultrasonic techniques, acoustic technique, etc. (Edwards et al., 2021). To overcome the above-mentioned limitations, chromatography can be used accurately classify all samples accurately and detect foreign materials effectively. It is an important bio-physical technique that enables qualitative and quantitative analysis of samples, and, when coupled with spectrometric techniques, facilitates the identification of separated analytes in a single run (Barberis et al., 2021). To enable consumers and prevent them from hazards chromatography can help in preventing all fraudulent activities. The purpose of this study is to examine the chromatography-based techniques that can be used for food fraud detection and food authentication. However, this literature review summarizes food fraud risks, and various frauds in different food supply chains. Hence, the current study aims to provide the latest source of information about food fraud risks, combating food fraud cases, separation and identification of complex matric of food, the establishment of food profiles of samples and traceability of the origin and mislabelling of the food, allowing the creation of reference databases of genuine foods to detect such distortions and can detect versatility of food and chromatographic techniques for food fraud and authentication. According to the literature, different types of techniques are used to detect food fraud cases making this process difficult, this review presented an idea of food fraud cases in public health as well as in industry and then provided side-by-side solutions through chromatography. So by establishing a setup of chromatography numerous samples can be quantified in the laboratory, supply chain, and through on-site screening.

2. Food fraud risks and threats to public health

Risk is defined as the chance of something (Oplatowska-Stachowiak & Elliott, 2017). Food fraud risk is of three types: direct, indirect, and technical harm to public health. Consumers are subject to direct risk when they intake lethal and carcinogenic contaminants that can harm a single exposure to the consumer. Indirect risk occurs when consumers intake contaminants for a long exposure time, and technical risk occurs when any technical issue arises, including mislabeling and the arrival of contaminant from the country of origin (Robson et al., 2021).

Food fraud may not directly endanger public health, but it has adverse effects on food quality, such as diluting alcohol with water or substituting ingredients or species. The presence of undisclosed contaminants in food supply chains can lead to food safety risks associated with fraudulent food practices. For instance, Al-Bratty et al. (2020) examined in Saudi Arabia that the caffeine concentrations were very high in energy drinks like Red Bull, Bison Berry, and Code Red. They were marketed with the concept that they can amplify energy levels in consumers. These beverages typically target consumers in the age group of 18 to 34 years with a focus on young adults, these consumers were diagnosed with health issues like nervousness, anxiety, agitation, insomnia, and palpitations reason behind that was caffeine along with paracetamol dissolved in an energy drink.

Similarly, Windarsih et al. (2022) studied the pangasius hypothalamus, which was a species of catfish and an excellent source of protein. Pork meat was mixed with pangasius hypothalamus meat as an adulterant. Adulterated samples were prepared by using many concentrations ranging from 0.5%–100%. Liquid chromatography-high resolution mass spectrometry (LC–HRMS) was used to determine a pork contamination concentration level of 0.5% in pangasius hypothalamus meat that was deteriorating its quality. Wang et al. (2019) studied duck meat has the same aroma as mutton. A gas chromatography–mass spectrometer (GC–MS) was used to determine duck meat concentration in mutton. An electronic nose was used to analyze odor and aroma in just a few seconds. *E*-nose identified 10% adulteration of duck meat in mutton, it was noted that public health was damaged by inferior quality meat. Zhang et al. (2022a) studied some fraudsters who blended peanut oil with less expensive oils such as soybean oil, palm oil, salad oil, or cottonseed oil in China. Chinese enterprises were using food safety across the supply chain as a food fraud vulnerability assessment tool, along with nonparametric tests and multiple compatibility analyses to identify instances of adulteration in edible vegetable oils. The existence of oleic acids (ranging from 36% to 67%) and linoleic acids (ranging from 15% to 46%) in peanut oil was linked to reduced cardiovascular disease risk and coronary heart disease. However, incorporating less expensive oils compromises the quality of peanut oil.

Cunha et al. (2020) studied canned meat containing pâtés, sausages, and whole meals, bisphenol A was determined. It is present in packaging material, and it seeps down into the food heating, storage, and at specific pH conditions. Results revealed that it poses a threat to fertility, lower birth weight, breathing issues, elevated anxiety and depression in children, diabetes mellitus, breast and prostate cancer, hypertension, and obesity at an earlier onset of puberty (Neo et al., 2022). In another study,

it was examined the feasibility of adulterants in vegetable oil by using a flash gas chromatography electronic nose in conjunction with machine learning. The qualitative analysis yielded favorable results with an accuracy of 1.000 (Tian et al., 2023).

Ji et al. (2023) investigated by collecting three samples of mare milk (female horse milk). It was observed in the study that the seller mixed cow milk with mare milk for profit. Different types of proteins (casein and histatherin) and metabolites (acetic acid and orotic acid) were used in milk samples as a detector and placed in a liquid chromatographer for hours and indicated cow milk concentration was as low as 1%. Ivanova et al. (2019) investigated the adulteration of cow milk with camel milk powder by ultra-high performance liquid chromatography (UPLC) was detected. Bovine beta-lacto globulin was used as a detector maker to indicate fraud in food. 20 samples of commercial camel powders were analyzed, and 8 were fully adulterated with cow milk. UPLC method might be applied as a reliable and helpful technique for the consistent authentication of camel products. The detection limit of cow milk was 5%. Windarsih et al. (2022) studied that in Singapore, the mislabeling of seafood products had serious issues. For individuals with seafood allergies, when consuming mislabeled seafood, their allergic reactions were triggered, causing breathing difficulties, hives, itching, swelling, abdominal pain, nausea, vomiting, and, in severe cases, anaphylaxis, a potentially fatal allergic reaction. Some seafood species have been linked to neurological impairment due to the strong neurotoxin tetrodotoxin, like monkfish. Mislabeling of Patagonian Toothfish *(Dissostichus eleginoides*) had potential harm to consumer health.

Cárdenas-Escudero et al. (2023) studied in Spain, adulteration of rice syrup in honey was detected. Consuming contaminated honey elevates blood sugar levels and increases the release of insulin hormones, leading to diabetes, abdominal weight gain, heightened blood lipid levels, obesity, and elevated blood pressure. Orrillo et al. (2019) studied black pepper adulterated with papaya seeds, which may cause stomach and liver issues. Food packaging may itself contribute chemical contaminants to the packaged contents to preserve food from various contamination sources and increase its shelf life. Chemicals that move into food from packaging can encompass oligomers derived from the structure of packaging and other impurities with ingredients. This complex combination found in food packaging may contain hazardous compounds, potentially posing dangers to consumers. Bergmann et al. (2023) investigated in Europe, High-performance thin-layer Chromatography (HPTLC) can detect up to seven out of ten genotoxic chemicals in food contact materials (paper board used as packaging material for cereals and beverages products including juices and milk). Moreover, the threshold of toxicological concern method can identify two out of ten chemicals using this approach for adults. The genotoxic chemicals detected include 2-nitrofluore, methylnitronitrosoguanidin, mitomycin, 4-nitroquinoline-1, etoposide, nalidixic acid, triglycidyl isocyanurate, 4-nitro-1,2-phenylenediamin, C.I. Disperse Orange nitrofurantoin, 5-chloro-2-methyl-3(2H)-isothiazolon, and tris(2-ethylhexyl) phosphate. Two chemicals were inactive: Orange 25 and TEP. Hence, HPTLC proved itself a new method for detecting bio-active chemicals in food packaging. Similarly, food supplements are regarded as safe products and are frequently used by various consumer groups without specific caution. However, there is a possibility of health risks linked to the consumption of supplements that contain undeclared substances. In Italy, a liquid chromatography-tandem mass spectrometry technique was utilized to detect and quantify various active molecules, including biogenic amines and natural alkaloids in herbal food, which, when consumed excessively, could pose health risks to consumers. Caffeine, phenethylamine, agmatine sulfate, and icariin were successfully separated and recognized with a high level of precision and satisfactory recovery rates ranging from 89% to 109%. This LC-MS/MS method can be easily used to test natural supplements to check the correct labeling and to protect consumers from food frauds and potential health risk (Elihasridas et al., 2023; Esposito et al., 2023; Kami, 2023; Khan et al., 2023).

Despite these facts, non-targeted screening and fingerprinting of the chromatography potential adulterants detected through chromatography is far better than targeted screening done traditionally, and it is important for emerging food fraud cases. Food fraud endangers public health either by its direct exposure to the form of drug dosage like paracetamol dissolved in energy drinks, considered safe for healing pain sensation, or indirectly deceiving consumers by contaminating milk samples with melamine. All these public health issues are further explained in Fig. 1. (See Tables 1 and 2.)

3. Food authentication based on chromatographic techniques

3.1. Liquid-chromatography (LC)

LC is a basic form of chromatography where a liquid serves as both the mobile and stationary phases with inert solid substances like silica gel, alumina, or cellulose supporting in a column (Gupta et al., 2020). LC requires fewer sample preparation steps and provides high sensitivity, high specificity, as well as high reproducibility for analysis of meat either in fresh or processed foam (Batool et al., 2023; Choudhary & Tahir, 2023; Stachniuk et al., 2021). China is home to over half of the world's fungal species. Wild edible mushrooms are highly sought after for their delectable taste and nutritional richness. Powdered mushrooms, when mixed with other ingredients, are commonly utilized as food additives. Unfortunately, there is a risk of adulteration with inedible wild mushrooms, as distinguishing between them becomes difficult in powdered form. Amanitas are among the most likely adulterants due to their abundance and distinct flavor (Xu et al., 2017). Analytical techniques, such as liquid chromatography–ultraviolet–diode array detection, are effective in quantifying toxins, particularly in pure Amanitas with high toxin concentrations. LC technique used for detection of adulterants potato starch, cassava starch, and corn starch in the lotus root powder identification of adulterated ingredients in lotus root. In another study food adulteration, which was a major worldwide issue alarming the safety of public health and the healthy development of food factories. The liquid chromatography-tandem mass spectroscopy technique was used for detecting fox meat in duck meat. The fox-duck proportion was 1.128, 3.347, 4.318, 8.207, and 12.027, respectively, in this way, LC helps in food authentication (Bai et al., 2023; Zhang et al., 2022b).

Similarly, Li, Wang, et al. (2021) studied the LC-MS/MS method incorporating the enzyme carbonic anhydrase 3, which was determined and verified to identify pork presence in processed meat products through the internal standard methodology. The pork content was assessed at final concentrations of 0.5, 1.25, 2.5, 5.0, 10, and 15 mg/mL.

Fig. 1. Symptoms in public health induced due to food fraud.

Table 1
Chromatography technique to detect food fraud (Novel technique expresses result in fingerprints).

Product	Instrument	Detection technique	Experiment	Result	Reference
Almond	HPLC-FLD	Fingerprinting combined with chemometrics.	Two experimental units were carried out one with natural almond and the other with almond custard cream. Extraction of the sample was carried out with water and acetone then centrifuged the sample. For the chemometric study, the chemometric method used, matrics of sample designed for HPLC-FLD chromatographic fingerprints.	Hazel nut and peanut fingerprints showed higher peaks as compared to almonds when the sample was adulterated.	(Campmajó et al., 2020b)
Thyme	Gas chromatography-orbitrap high-resolution mass spectrometry and chemometrics	Fingerprinting	GC-HRMS-based fingerprinting was applied in the thyme of different regions to compare disinfected and non-disinfected thyme. Fingerprint analysis was carried out with chromatography combined with orbital mass analyzer.	20 markers were considered reliable for sterilized and non-sterilized thyme samples. Fingerprints revealed that thyme depends upon environmental conditions.	(Rivera-Pérez et al., 2022)
Paprika	HPLC-FLD	Fingerprinting	From different countries, 122 samples of paprika were collected. Solid-liquid extraction was carried out using water and acetonitrile in a ratio of 20:890 *v*/v. HPLC-FLD is used as paprika markers.	FLD is used as an alternative to UV and MS detection previously used for non-polymeric chemical compounds and phenolic molecules. HPLC-FLD was used as a chemical descriptor to identify the origin and variety of paprika. It was used to detect fraud in paprika. Fingerprints varied according to variety and adulterant.	(Campmajó et al., 2021b)
Saffron	GC	Chemometrics-assisted isotope ratio fingerprinting	The sample was analyzed with GC–MS for saffron authentication and instruments using an isotope and food fingerprinting method. Adultrantrs of saffron like calendula, sativus style, rubia, and safflower were analyzed.	Fingerprinting showed 100% accuracy presenting a clear difference between saffron and adulterants.	(Ghiasi & Parastar, 2021)
Paprika	HPLC-FLD	Second-order fingerprints	To determine paprika adulteration 6 samples from different regions were collected. Samples were divided into pairs treated with fingerprints collected at different wavelengths using chromatography and main data fused in spectral and time dimensions. Data was then analyzed with the partial least square method (PLS).	PLS result showed a paprika adulteration prediction of 20.28%.	(Campmajó et al., 2021a)
Vegetable oil samples	Chemometric	FIA–HRMS fingerprinting	To determine vegetable oil samples before chemometric analysis fingerprints were taken and analyzed sample characteristics. Ions peaks analyzed carefully negative and positive ions of olive oil showed different results.	Olive oil is used as an adulterant in oils added to improve taste having polyphenolic compounds exhibit ethanolic extract.	(Campmajó et al., 2022)
Coffee	Untargeted HPLC-UV-FLD	Fingerprinting and chemometrics	Detection adulteration was carried out by solid-liquid extraction, as extracting solvent methanol-water was used. Fingerprints were obtained through reverse-phase column chromatography.	Adulterants detected through the result of partial least square regression giving a 100% sample classification rate.	(Núñez et al., 2021a)
Tea	High-throughput flow injection analysis	Spectrometry (FIA-MS) fingerprinting	Sample prepared from 101 different tea samples along with 20 chicory samples.	When the sample was infused in hot water, the ionization of the sample showed positive and negative results. Positive ionization showed a higher peak in fingerprints. From peaks of samples, adulteration of tea varieties was identified.	(Vilà Romeu et al., 2022)
Hen Eggs	Chemometric method	HPLC-UV fingerprinting	Eggs were classified into four samples according to their production. HPLC fingerprinting was used to detect egg classification according to labeled type. Egg size was also investigated—reverse phase separation was used through principal component analysis.	Egg classification showed 82.6%. Chromatography at 250 nm showed beneficial results for labeled eggs. Fingerprinting also showed egg phytochemical content.	(Campmajó et al., 2019)
Paprika	Chemometric	HPLC–FLD fingerprinting	From six different regions, 72 samples were prepared. Paprika flavor, pungency degree, and region of Guizhou, China.	HPLC–FLD fingerprinting identified adulteration in the Guizhou region.	(Sun et al., 2023)
Walnuts	HPLC-DAD	HPLC chromatography	26 walnut samples were prepared from the local market. Phenolic compounds are extracted through ultrasound ultrasound-assisted technique.	Eighteen types of phenolic compounds were determined from 26 walnuts sample through chemometrics, and a robust partial least square–discriminant analysis.	(Kalogiouri & Samanidou, 2021a)

(*continued on next page*)

Table 1 (*continued*)

Product	Instrument	Detection technique	Experiment	Result	Reference
Tomato Sauce	GC	Volatile fingerprinting	Tomato sauce was analyzed with GC and flame ionization technique. The sauce had colloidal suspension that was analyzed through flow fluid fractionation.	Fingerprints obtained through GC showed the complexity of the sauce matrix.	(Zappi et al., 2022)
Olive oil	Chemometrics	Chromatographic fingerprinting	A total of 65 samples of variety Arbequina was prepared using soft independent modeling of class analogy technique to improve result fusion method applied at high and low concentration.	Chromatographic fingerprinting showed that 3 samples differ from Arbequina's original variety.	(Vera et al., 2019)
Organic compounds in animals	Headspace-gas-chromatography ion-mobility spectrometry	Chromatography fingerprinting	Volatile organic compounds were identified in seven different animal species using their muscle tissue. Headspace-gas-chromatography ion-mobility spectrometry was used to identify 60 VOCs.	The drift time, retention time, and molecular weight showed different fingerprints. Fingerprints maintained better stability among the same species.	(Li et al., 2022)
Non-dairy milk	Matrix-assisted laser desorption ionization mass spectrometry	lipids fingerprinting	Four types of milk samples were prepared including bovine milk, soya milk, coconut milk, and organic bovine milk, to detect adulteration mass spectrometry was performed.	The lipid profile (triglyceride) showed adulteration of coconut and soya milk in bovine milk when the sample was diluted in a ratio of 1:4, dilution showed adulteration.	(England et al., 2020)
Honey	LC methods	Chromatographic fingerprints	A total of 136 honey samples were prepared, and a simple experiment was carried out by dissolving 1 g of honey in 10 g of water then the chromatography separation technique was applied.	Chromatographic fingerprints showed classification among honey verities and gave a peak of retention time.	(García Seval et al., 2022)
Sesame oil	GC–MS	Aromatic fingerprinting	To adulterate sesame oil soybean and corn were added in four different formulations ranging from 25 to 100% then metal oxide semiconducting, GC–MS, and an electric nose were used to detect adulteration in the sample. For statical analysis, support vector machine (SVM) and artificial neural network (ANN) were used.	SVM gave up to 0.987 and 0.977% specific results and ANN gave 0.949 and 0.953 sensitivity results.	(Aghili et al., 2023)
Plant food supplements	Ultra-high-pressure liquid chromatography	Chromatographic fingerprints	2–3 regulated plants were taken from them test sample was prepared. Chromatography fingerprints were taken using the diode array detection technique at a wavelength of 254 nm. Plants were screened into two parts as toxic and regulated plants and their response was recorded according to retention time and mass spectrometer spectra.	*Aristolochia fanghi* and *Ilex paraguariensisis* were declared as reference plants and positive and negative results were obtained depending upon the toxicity of the plants. Some plants were forbidden others mentioned on the packaging of herbs for indication.	(Custers et al., 2017)
Goat milk powder	GC–MS	GC–MS fingerprints	Almost 50 types of volatile compounds were identified in goat quid fraction samples using NMR and GC–MS chromatography techniques.	The quality characteristics, flavor, and chemical composition of milk goat samples were identified to compare fraud in pure samples and impure samples.	(Sanchez et al., 2021)
Duck eggs	Ultra high-performance liquid chromatography-high resolution mass spectrometry	Chromatographic markers	Fraud in the egg industry between two breads of duck such as sea duck and cage duck was performed using ultra-high performance LC–HRMS from markers of reference standard. Nervonoyl-d-*erythro*-sphingosine, n-behenoyl-d-*erythro*-sphingosine, and 1,2-dipalmitoyl-*sn*-glycero-3-phosphocholine were elected as markers for sea duck eggs.	Sea duck egg markers when used in 48 samples of fresh duck eggs, markers resemble more with sea duck eggs than cage duck eggs because of the fatty acid nature of markers indicating fraud in the poultry industry.	(Dong et al., 2021)

The limit of detection (LOD) and limit of quantification (LOQ) were determined based on signal-to-noise ratios of 3:1 and 10:1. Different types of meat products were quantified through this method. Similarly, powdered tea extracts with LC or colorimetric in quality control analyses of powdered tea extract. This study aimed to enhance existing strategies by investigating the possibilities of an alternative gas chromatographic method. Nineteen powdered tea extracts with varying standardizations were examined in comparison to certified tea leaves. Several undesired compounds were detected, such as anti-oxidants, organic solvents, and intermediates of the catechin synthesis in huge amounts (García Seval et al., 2022; Zaman et al., 2023). This technique helps in the authenticity of tea extract and ensures the safety and improved quality of the product. LC is versatile in its ability to analyze a wide range of analytes ranging from small inorganic ions to large biomolecules. LC has been utilized for identifying adulterants of potato starch, cassava starch, and corn starch in lotus root powder, assisting in the detection of fraudulent ingredients in lotus root products, and addressing concerns regarding food fraud in the industry. To overcome challenges faced in LC and enhance the speed, sensitivity, and resolution of LC, several advanced techniques have been developed including HPLC and GC–MS. These methods aim to achieve accurate results efficiently (Manzoor, Rasool, Khan, Anjum, & Parveen, 2023; Sri et al., 2020; Sultana et al., 2023). There are several techniques used as a combination to provide more efficient and advanced results, such as LC combined with MS (LC-MS) and LC-HRMS, it was noted that when these techniques combined a large number of samples quantified at a time with higher efficiency to study metabolic profiling of the samples either from plants and from industry, isotopic analysis was also carried out using LC-IRMS (Isotope-ratio mass spectrometry) that is an advance method of LC chromatography and used in controlling the laboratory repeatability. Nuclear Magnetic Resonance is considered as advanced technique to detect the structure of the molecules. A further innovation is that when LC × LC

Table 2
Use of chromatography in different industries to capture food fraud concerning health.

Food Category	Adulterant	Adulterant percentage	Techniques	Harmful effects	Reference
Milk and Milk products					
Cow milk	>5%	–	UPLC	Allergic issues	(Li, Zhang, et al., 2021)
Milk	Hydrogen peroxide	-	HPLC	Vomiting, neurological problem	(Ivanova et al., 2019)
Ice cream	Sunset, quinolines yellow, and tartrazine	7.1% tartrazine, 6.51% yellow Quinolines	HPLC	Gastrointestinal issues	(Rahnama et al., 2022)
Ice cream	Vanillin	–	GC	Irritating, cancer, changing in chromosome	(Homayouni et al., 2018)
Cheese	Whey protein	–	LC	Nausea, fatigue, acne	(de Oliveira et al., 2022b)
Clarified Butter	Vegetable oil	6.7%	GC	Low quality	(Pathania et al., 2020)
Butterfat	Foreign fat and oils	–	GC	Neurological problems	(Naviglio et al., 2017)
Butter	Oil/fats/margarine	Above 5%	UHPLC	Quality issues, headache, fatigue.	(Sun et al., 2021)
Cow ghee	Vanaspati	–	GC	Cholesterol level increased	(Roy et al., 2022)
Butter	Sunflower oil, rapeseed oil	1.2%	GC	Nausea, fatigue, acne	(Szabóová et al., 2018)
Meat					
Fish meat	Pork meat	0.5%	LC	Religious issues	(Windarsih et al., 2022)
Salmon	rainbow trout	0.62%	–	Bacterial infections, caused by mycobacterium, Salmonella, vibrio	(Augusto et al., 2020)
Poultry meat	Soy, milk, egg white protein.	Allergic protein	LC	Food poisoning is caused by salmonella and campylobacter.	(Montowska & Fornal, 2018)
Mutton	Duck meat	–	GC	Reduce protein levels, cardiovascular disease, cancer, and diabetes.	(Wang et al., 2019)
Beef ball	Wild boar, chicken	–	LC	Halal/non-halal, cardiovascular diseases.	(Pranata et al., 2021)
Herring, cod fillet	Water, protein, carbonates	–	IC	Increase cholesterol level.	(Bisenius et al., 2020)
OILS					
Palm oil	Lard	–	HSGC	Religious issues, gut problems	(Putri et al., 2020)
Olive oil	Sunflower oil	5, 10 and 15%	Reversed-phase high-performance liquid chromatography	Quality decreased	(Bakre et al., 2015)
Peanut oil	Rapeseed oil	–	GC	Decline nutritional value	(Tian et al., 2019)
Sesame essence oil	Cheaper vegetable oil	<5%	HSGC	Quality decreased	(Dou et al., 2022)
Olive oil	Soya oil	25%, 50%, 75%	GC	Skin allergic, gut problem	(Zhou et al., 2021)
Juices and nectars					
Persian lime juices	Iso-citric acid, citric acid, malic acid	Industrial and non-industrial criteria above 300 citric acids	LC	Flue, throat problems, respiratory issues.	(AliAbadi et al., 2022)
Citrus juice	Quality citrus juice	Low quality	UPLC	Asthma, allergic issues	(Jandrić et al., 2017)
Orange juice	Mandarin, tangerine, lemon, grapefruit.	–	Ultra-fast GC	Increase the number of impurities and quality low.	(Różańska et al., 2018)
Orange juice	volatile metabolites	–	GC	Effect eye, nose, and throat irritation	(Li et al., 2020)
Sweet orange juice	Volatile organic compound	–	HSGC	Nausea, headaches	(Zhou et al., 2020)
pomegranate juice	grape and apple	–	GC	Quality decreased	(Kalogiouri et al., 2024)
Berries juice	Anthocyanin	–	LC	Antioxidant stress, cardiovascular diseases	(Avula et al., 2023)
Honey	Sugar cane, corn syrup.	–	HSGC	Diabetic, obesity	(Arroyo-Manzanares et al., 2019)
Honey	Other sugar	−11.2% to −25.1%	LC	Pollen allergy,	(El Hawari et al., 2021)
Bakery					
Quinoa flour	Wheat, rice	5%	HSGC	Low quality	(Yang et al., 2022)
Wheat flour, chestnut flour	Mycotoxins	–		Vomiting, fatigue, bowel problems,	(Yang et al., 2022)
Almond flour	Hazel and peanut	–	HPLC	Pose a hazard to human health	(Campmajó et al., 2020b)
Cocoa powder	Carob, soy flour, and chicory	–	HPLC	Nervousness, constipation.	(Greno et al., 2023)

(*continued on next page*)

Table 2 (*continued*)

Food Category	Adulterant	Adulterant percentage	Techniques	Harmful effects	Reference
lotus root powders	Starches	–	LC	Allergic reaction	(Bai et al., 2023)
Confectionary					
Candy	Porcine-derived components in gelatin, donkey gelatin	0.07%,0.12%	HPLC	Haram, stomach discomfort	(Zhu et al., 2023)
Rocky candy	Synthetic dyes	26.53%	HPTLC	Gastric issues	(Sadeghi et al., 2020b)
Chewing gum	ED drugs	–	LC	Cancers	(Mohd Yusop et al., 2021)
Chocolate	Melamine	0.032 to 2.692 mg	HPLC	Bladder, kidney stone	(Abedini et al., 2021b)
Chocolates	Cocoa butter, other fats	–	–	Sleeplessness, fast heartbeat	(Khaleghi Yazdi et al., 2021)

combined it was noted that a higher peak was observed because it combined two separation mechanisms another technique was recycling liquid chromatography C↻LC) helps in detecting the chemical composition of the polymers it can analyze the large columns, reaction modulators also played an important role to detect nanoparticles in the samples in compounds that are sensitive to the light, valves, and valves based innovation resulted in the improved output through LC (Biswas et al., 2023; Broeckhoven & Desmet, 2020).

3.2. High-performance liquid chromatography (HPLC)

HPLC is an analytical technique employed for the rapid separation, structural and functional analysis, and purification of molecules. It measures accurately separating and identifying various molecules such as amino acids, carbohydrates, lipids, nucleic acids, proteins, and steroids. In HPLC, the mobile phase travels through columns under pressures ranging from 10 to 400 atm while maintaining a high flow rate of 0.1 to 5 cm per second. In this technique, the incorporation of small particles and the application of high pressure on the solvent flow rate enhanced HPLC separation power, and the analysis can be completed within a short time (Coskun, 2016). However, the HPLC method may not meet certain analytical requirements, such as the determination of complex samples like biological samples, degradation products, impurities, formulation excipients, drug metabolites, and drug isomers. Challenges in the HPLC method arise regarding the determination of analyte at low concentrations (0.1%), the speed of analysis, and the resolution per unit time. Certain analytical requirements (Precise determination at trace levels without any pre-treatment step poses a challenge) cannot be met by the HPLC method, particularly when dealing with complex samples such as biological samples, degradation products, impurities, formulation excipients, drug metabolites, and drug isomers. HPLC is a destructive, time-consuming, costly, and labor-intensive techniques, that require expertise.

Núñez et al. (2021b) studied chromatography fingerprinting has recently attained interest when performed through high-performance liquid chromatography techniques with fluorescence detection (HPLC-FLD). Phenolic/polyphenolic food extracts, when analyzed in application have proven exceptional performance. For instance, the origin, variety, and roasting degree of coffee were successfully determined as chemical descriptors to address HPLC-FLD fingerprints. HPLC was used as a detector and used phenolic and polyphenol compounds as markers to detect foreign material fraud in paprika with an accuracy of 97.9%. HPLC-FLD fingerprints were employed to determine the difference between nuts. Partial least squares regression-discriminant analysis was used to identify and quantify the adulteration of hazelnuts and peanuts in almond products such as almond flour and almond custard cream that was used as a fraudulent act. HPLC extraction was employed to obtain various types of nuts in almond products. The Ideal time for the extraction process was 30 min at 3400 rpm using a centrifuge machine (Campmajó et al., 2020a; Zhang et al., 2022a). Similarly, a total, of 18 distinct polyphenols, including gallic acid, sinapic acid, and caffeic acid, were identified. The relative standard deviations for both within-day and between-day assays were below 6.3–11.1, which shows high accuracy ranging from 86.4% (sinapic acid) to 98.4% (caffeic acid) and from 90.1 (gallocatechin gallate) to 100.6% (gallic acid). Results revealed that this technique helps in the identification of the geographical origin and proved helpful in the authentication of walnuts from fraud (Campmajó et al., 2021a; Kalogiouri & Samanidou, 2021b).

HPTLC was employed to detect adulteration of hypolipidemic drugs in five distinct herbal tea samples: *ginkgo biloba*, lotus leaf, Chrysanthemum Apocynum, and gynostemia. A standardized HPTLC method was utilized, wherein silica gel plates were used to separate sample extracts. This method enabled selective detection screening for the desired chemicals with an accuracy ranging from 71 to 91% and proved helpful in determining hypolipidemic drugs (Wang et al., 2023). HPLC has been shown to successfully detect adulteration in herbal tea (hypolipidemic drugs), paprika (phenolic and polyphenol compounds), and nuts like almonds, hazelnuts, walnuts, etc.

3.3. Gas chromatography (GC)

GC is a set of analytical separation methods employed for analyzing volatile substances in the gas phase. In this technique, the components of a sample are dissolved in a solvent and vaporized to separate the analyte by distributing the sample between two phases: a stationary phase and a mobile phase. The mobile phase, typically a chemically inert gas, carries the analyte molecules through a heated column. Unlike other forms of chromatography, GC does not rely on the mobile phase for interacting with the analyte. GC is one of the unique forms of chromatography that does not require the mobile phase to interact with the analyte. GC can be categorized based on the state of the stationary phase into gas-solid chromatography, where the stationary phase is solid, and gas-liquid chromatography, which employs a liquid as the stationary phase. GC-based techniques provide good precision & accuracy, good resolving power, and sensitivity even with a few mg of sample. However, GC has high sensitivity, low detection limit, and takes too much time for analysis (Kaur & Sharma, 2018; Mitran et al., 2019).

GC is used as a potent method for precisely separating and detecting volatile organic compounds. In food inspection, ensuring the quality and safety of edible oils is a significant challenge. Therefore, it is essential to develop practical methods for determining adulteration in edible oils. These chromatographic methods are based on the determination of trans sterols, triglycerides, fatty acids, hydrocarbons, and other components to detect fraud (Jabeur et al., 2016). Different GC-based analytical techniques have been used to identify adulteration in edible vegetable oils, including GC–MS (Aghili et al., 2022).

Studies indicate that basmati rice is now a prime target for fraudulent schemes. Hence, the headspace GC–MS technique was used to detect

fraud in basmati rice, and this food commodity faced intense food fraud in the COVID-19 era. The chemometric model showed fingerprints of adulterants and classified basmati rice with 0.99% accuracy (Shannon et al., 2021a, 2021b). The chemometric method and electronic nose were used to detect volatile organic compounds in 11 lemon juice samples; fraud was carried out by the addition of excessive undeclared sugar and water, followed by the addition of lemon pulp and other citrus components. Potential adulterants and additives determined in lemon juice with this non-destructive technique with >95% accuracy to authenticate plant-based natural products in the market (Mohammadian et al., 2023a). GC combustion and isotope ratio mass spectrometry detected four types of foreign particles marigold flower, safflower, rubia, and saffron GC–MS with robust nuclear magnetic resonance in the identification of metabolites and volatiles in goat milk powder (Ghiasi & Parastar, 2021). NMR determined 44 metabolites in the solution. GC–MS was able to identify >50 volatiles like alcohols, alkanes, alkenes, ketones, aromatics, aldehydes, sulfur compounds, and esters and proved it an efficient technique in food authentication (Sanchez et al., 2021). GC has been proven effective in detecting adulteration in edible vegetable oil (fatty acids, trans sterols, triglycerides, and hydrocarbons), Basmati rice (low-quality rice), lemon juice (excessive undeclared sugar, orange juices, and extra water), and goat milk powder (marigold flower, safflower, Rubia). Recent advances in the field are combining HPLC with MS that must be highly selective to tackle fraud in the food along with its verification, portable instruments can also be designed for onsite verification of the fraud these instruments are called miniaturized and portable instruments, advancements in the stationary phase of the HPLC also helps in modifying the procedure like mixed-mode, chiral and HILIC phases are using to detect versatility of the fraud (Butler et al., 2021).

3.4. Affinity chromatography

Affinity chromatography is a technique for separating biochemical mixtures by exploiting highly specific interactions between entities like antigen and antibody, enzyme and substrate, receptor and ligand, or protein. It yields high purity due to interactions between the ligand and naturally occurring regions or sites present on the target surface, achieving nanomolar affinities comparable to industry standards such as protein A and antibodies, typically in the 10–50 nm range. Sample volume limitation, costly ligand, and protein loss (Ahmed, Amjad, Mehwish, & Anwar, 2023; Łącki & Riske, 2020; Mansoor et al., 2023).

Affinity chromatography can detect mycotoxins entering the food chain of the human through bioaccumulation in animal products such as milk, meat, eggs, and cheese known for their high toxicity and thermal stability. Due to their teratogenic, toxic, carcinogenic, and endocrine-disruptive properties, mycotoxin contamination in food poses significant health risks to humans and animals alike. Enzyme-linked immunosorbent assay and AC are commercially available to detect these toxins. A sensor developed for this purpose enables the detection of ochratoxin A at concentration levels as low as 0.75 $ng.mL^{-1}$, it proved helpful authentication of plant-based products by checking their labels (Mahmoudpour et al., 2019). Likewise detecting pesticide residues in food is crucial for maintaining chemical food safety, given the toxicity of these compounds and the uncertain effects of their metabolites. The proliferation of affinity sensors tested on real samples suggests that this method is ready for validation to monitor pesticide levels in food. Using a simple extraction method on potato samples, paraquat was effectively detected, with a limit of detection of 5.44×10^{-9} M through its sensors, and helped in the assessment and monitoring of pesticide levels (Capoferri et al., 2018).

Another important factor is food allergies resulting from immune responses triggered by exposure to specific antigens, representing significant safety concerns in developed nations. These allergies affect 1–10% of the global population, with children being particularly vulnerable. Electrochemical affinity biosensors including immunosensors and those using synthetic DNA or RNA sequences, aptameric techniques have been developed to detect major allergenic proteins found in peanuts, eggs, gluten, milk, and shrimp, as well as to identify milk adulterations with other animal milk or colostrum. They enable the determination of target analytes at concentrations as low as a few $ng.mL^{-1}$ - $mg.kg^{-1}$. Notably, these methods have achieved remarkably low LOD as low as 47 $pg.mL^{-1}$. This accuracy proved a helpful analytical tool for the determination of allergens in daily life and for detecting adulterants where needed (Campuzano et al., 2020a). Affinity Chromatography is notably expensive due to the requirement of producing highly purified proteins before isolating the target protein. Its applications include Identifying major allergenic proteins found in peanuts, eggs, gluten, milk, and shrimp. Additionally, it facilitates the detection of milk adulterations with other animal milk or colostrum pesticides and mycotoxins in milk, meat, eggs, and cheese. It can detect adulteration at concentrations as low as $ng.mL^{-1}$ and even $pg.mL^{-1}$ (Campuzano et al., 2020b).

3.5. Thin layer chromatography (TLC)

TLC involves the separation of compounds on a thin layer of adsorbent material, typically consisting of a silica gel coating applied to a glass plate. It's a fast, straightforward, cost-effective method with high sample throughput and offers a wide range of mobile phase options. TLC requires minimal sample preparation, offers qualitative analysis rather than quantitative, and lacks automation in the process (Ramraje et al., 2020).

Similarly, quality control, nutritional analysis, and the monitoring of harmful residues in products sourced from bees have become crucial topics for producers and consumers alike. As awareness grows regarding their potential health advantages, bee-derived products rich in bioactive compounds are experiencing increased demand and popularity. TLC methods were employed in the quality assessment, authentication, and chemical characterization of bee-derived products. These methods aim to aid researchers in the field of bee-product chemistry by leveraging the benefits of TLC to identify and mitigate fraudulent activities in bee-product manufacturing (Milojković-Opsenica et al., 2022). In another study, saffron was extracted from the stigmas of *Crocus sativus*, which is a flavoring agent in international food markets, making it susceptible to various forms of fraudulent activity. This study introduced the application of thin-layer chromatography combined with image analysis (TLC-IA) and chemometrics techniques to authenticate saffron and promptly identified seven potential adulterants. SD for each sample was reported as follows: madder (3.2), quinoline yellow (3.8), tartrazine (4.1), sunset yellow (4.3), sumac (3.4), saffron (3.9), turmeric (4.5), and safflower (3.3), this technique proved help fill in the quantification of Iranian based saffron and to tackle fraud (Sereshti et al., 2018). A novel HPTLC technique utilizing silica gel plates impregnated with caffeine was developed for the detection of eight commonly encountered fat-soluble azo dyes, which are often illicitly added to spices, spice blends, pastes, sauces, and palm oils. Detection and quantification limits were established at 2–3 and 6–9 ng/zone. This novel method helps in the separation of 23 separations of samples in a very short time of 5 min through screening (Schwack et al., 2018).

Likewise, column chromatography, ion-exchange chromatography, gel-permeation (molecular sieve) chromatography, paper chromatography, dye-ligand chromatography, hydrophobic interaction chromatography, and pseudo affinity chromatography represent a variety of chromatography techniques available. While these techniques have their applications, they are considered less practical compared to others. Currently, HPLC and UPLC stand out as innovative methods, particularly in detecting food fraud. Looking forward to these advanced techniques are anticipated to play a central role in future endeavors to combat fraud.

4. Food fraud network and supply chains

Food fraud in the supply chain is practiced enormously, and its tendency is increasing day by day. To overcome this issue, rapid testing methods like chromatography are adopted. To tackle the food fraud network, chromatography with spectrometry is one of the dominating methods that have been implemented in the supply chain of basic four foods, like cereals, beverages, confectionery, and bakery. On an industrial scale chromatography adopted and industrial behavior on chromatography implementation was noted by conducting interviews and workshops to monitor the supply chain (Galindo-Luján et al., 2023a). With advancements in industrialization and the shifting of consumers to ready-made products concerns about food safety increase, the importance of chromatography in the food industry for analyzing food constituents and waste chemicals, as well as changes in food taste, packaging, and odor composition was analyzed (Casado et al., 2024; Osmani, 2021; Schoenmakers, 2009).

4.1. Food fraud detection in cereals supply chain

In the cereals supply chain, the most frequent fraud practiced was the introduction of common wheat to durum wheat. The permitted limit for such an addition is almost 3%, as exceeding this threshold disrupts the quality required for pasta made from durum wheat. In the case of Canada, this addition of common wheat has been reported as its price was 25% lower than durum wheat, leading to fraudulent activity. The bread has also been adulterated with other flour not indicated on the label. Another fraudulent practice involved mixing white rice with different cereals, i.e., Chinese white rice was reportedly combined with Korean white rice. Hence, LC has been used in screening the supply chain of organic and conventional crops (Suman et al., 2021). In recent years, quinoa grain has become widely available worldwide either in its whole form as a component of healthy diets or as a crucial element in the formulation of gluten-free and nutrient-enriched food items. This versatility makes it a highly favorable option for individuals managing this condition and this grain has the potential to tackle world food security highly vulnerable to fraud having high nutritional value it was mostly adulterated with cheap grains, a combination of LC with ultraviolet absorption diode array detection and chemometrics techniques was used for determining adulteration chromatographic profile of the quinoa grains showed that commercially available quinoa grains varieties like white, black, red and royal were easily classified based on different composition through fingerprints of chromatography proving its advantageous over capillary electrophoresis-ultraviolet absorption diode array detection technique used previously in quality control of quinoa grains and may be adapted and used in protein extraction through foodstuff usingfingerprints (Galindo-Luján et al., 2023b). This was considered important for the industry due to bioactive compounds and saponins concentration explained in Fig. 2.

Similarly, liquid chromatography-mass spectrometry (LC-MS) was considered a reliable tool for detecting gluten peptides in rye, wheat, oats, and barley. In dried products, 13–16% of protein identifications were gluten proteins: 94 gluten proteins (13% of total protein identifications) in barley-containing products and 75 gluten proteins (14%) in wheat, barley, and oats-containing products. Results showed that peptides with immunotoxin epitopes were found and LC-MS showed authentic results to determine gluten peptides in food although having complex processing even in products baked and containing milk (Li et al., 2019). Similarly, gluten free and non-gluten free flour was separately classified using GC–MS coupled with automated machine learning framework extraction of liposoluble compounds was first done, and then samples were analyzed using chromatography based on the botanical origin of the cereals. It was noted that almost 85.71% of samples were correctly classified, separation of gluten free and non gluten free varieties further helped in making separate products out of their varieties (Pastor et al., 2022). A two-tiered system of analysis was used to tackle rice fraud. There are twenty-nine different varieties of Basmati officially recognized under the Seeds Act of 1966 for export from India. Near-infrared spectroscopy and headspace solid-phase microextraction GC–MS techniques have proven effective in both screening and

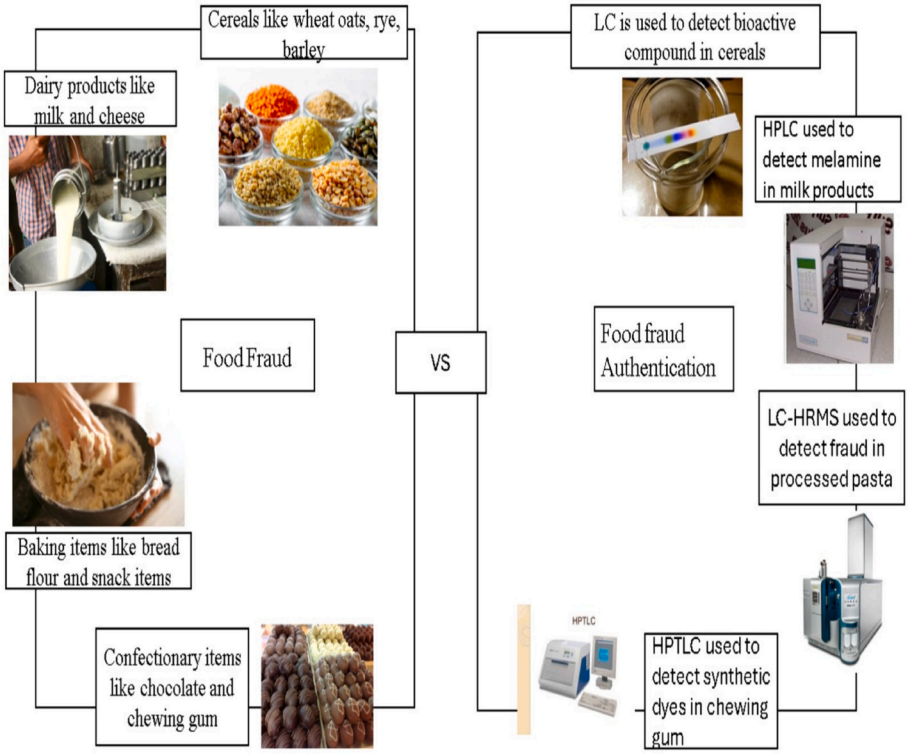

Fig. 2. Food fraud in industries and its possible authentication methods.

confirming the presence of adulterant samples of Indian Basmati rice. The chemometric model showed fingerprints of adulterants and classified basmati rice with 0.99% accuracy help in onsite screening of the fraud to save consumers (Shannon et al., 2021).

.In another study, liquid-liquid extraction combined with dispersive liquid-liquid microextraction has been created and verified for extracting and concentrating nine types of residues of pesticide from specific cereals. High-performance liquid chromatography-diode array detection was used in the detection, and quantification limits ranged from 0.16 to 0.60 $ng.g^{-1}$ and 0.53 to 2.0 $ng.g^{-1}$ along with extraction recoveries ranging from 55 to 90%. This method was applied to various cereals such as wheat, buckwheat, corn, barley, soya, rice, chickpea, and semolina (Abbaspour et al., 2019). Food fraud in cereals targets a large number of the population because wheat is the staple food for many countries, specifically Asian countries. So, fraud in grains will have many harmful effects on consumers later on. Grain variety, origin, bioactive compounds, and specific genomic structure that would be specifically altered have been detected through chromatography and its types, making cereals safe for consumption (Suman et al., 2021). Similarly, LC-HRMS was used to distinguish between the cultivars of wheat and spelt that help in the testing of food fraud and food adulteration, a spectrum was obtained to analyze fingerprints of chromatography. Fingerprints of food to identify tested samples were recorded in the wet lab component using this non-targeted method while the dry lab component used a conventional neural network, to classify and identify the results a matrix was developed named as D score that revealed that samples were correctly analyzed and not mismatched thus reducing the risk of mismatching of varieties proving this technique useful in quantifying the metrics of cereals that were mismatched (Nichani et al., 2022).

4.2. Food fraud detection in the beverage industry

In the beverage industry, the chemometric method and electronic nose were used to detect volatile organic compounds in 11 lemon juice samples; fraud was carried out by adding excessive undeclared sugar and water, followed by introducing lemon pulp and other citrus components. Potential adulterants and additives determined in lemon juice with this non-destructive technique with >95% accuracy to authenticate plant-based natural products in the market. *E*-nose can detect fraud in lemon juice non-destructively, along with separation of the product from its counterpart components this new method helps in detection of the fake items in the market because the e-nose works fast and does not separate the volatile components (Mohammadian et al., 2023b).

Similarly, In the Netherlands, the supply chain of milk exhibits a low to medium level of vulnerability to fraud although the specific factors influencing this vulnerability vary across different tiers of the chain including farmers, processors, and retailers (Yang et al., 2019). In addition, The bottom-up proteomic and shotgun approach utilized in the LC-MS/MS method proved to be both simple and effective in identifying fresh cheeses adulterated with whey concentrations exceeding 10% and also detecting adulteration in fresh cheeses made from sheep or goat milk and further validation is necessary, particularly in selecting additional marker peptides (de Oliveira et al., 2022a; Yang et al., 2019). Further, melamine is increasingly being used as a food adulterant, despite its known health risks. The adulteration of dairy products with melamine continues to boost protein content. Detection of contamination of melamine in chocolate powdered milk achieved through high-performance liquid chromatography. The LOD and LOQ for melamine are 0.017 and 0.052 μg/mL. The rate of recovery at a level of fortification of 1–2 mg/kg ranges from 89.20% to 95.69% (Abedini et al., 2021c). Hence it can be concluded that various forms of food fraud, such as the addition of volatile organic compounds, and the adulteration of milk and cheese with melamine, can be addressed with 89.20% to 95.69% detection accuracy using chromatography techniques.

Similarly, allergy caused by cow milk is the most prevalent food allergy, the primary allergen in milk is casein developed through a rapid digestion method employing trypsin immobilized on hairy polymer-chain hybrid magnetic nanoparticles, which is the latest type of immobilized trypsin, it helps in shorten the digestion time and enhance the digestion efficiency help to identify milk allergens using ultrahigh-performance liquid chromatography-tandem mass spectrometry even in highly baked products, LOQ were 0.38–0.83 μg/g, and their recoveries ranged up to 86.1%, with relative standard deviations of <11.0% (Qi et al., 2019). Milk adulteration is a very tragic problem because it is consumed by a large number of the population, it was studied that goat milk was adulterated with horse milk for economic gain due to its cheap cost, LC-HRMS was used to detect it along with chemometrics. When the principal component analysis was carried out goat milk and horse milk were separately distinguished through chemometrics so it was concluded that through this approach milk adulteration with any other milk source can easily be tackled (Windarsih et al., 2024).

4.3. Food fraud detection in the baking industry

In the baking industry, the hydrophilic interaction liquid chromatography-tandem mass spectrometric method was utilized for quantifying acrylamide in food, primarily targeting gingerbread samples with high sugar contents, the method was applied to assess acrylamide level. Acrylamide concentrations in these samples ranged from 20 to 667 μg/kg all falling below the benchmark levels established by the European Union. The method exhibited satisfactory accuracy up to 105% and a precision of 7.6%, with LOQ set at 20 μg/kg (Tölgyesi & Sharma, 2020). Similarly, this technique was used to check the adulteration of rye and wheat in bread production, for each variety a specific biomarker was designed to check the correct species present in each type of product, it works through in silico digestion along with the proteomics method. It proved helpful in detecting the adulteration of unlabelled products in the market (Bönick et al., 2017). In the production chain of the pastries and biscuits assessment was carried out to tackle fraud and to control safety threats to the product bulk and compound-specific IRMS was carried out by using specific markers like $\delta^{15}N_{bulk}$, $\delta^{15}N_{leucine}$, and $\delta^{15}N_{proline}$ specifically designed as isotopic fingerprints to detect mycotoxins in the biscuits coming from the wheat that was used during its processing, it was noted that pesticide reduced after the processing predicted that IRMS proved helpful for authentication of biscuits (Giannioti et al., 2024). Baking items like snacks, biscuits, cookies, bread and pastries can be quantified using chromatography and made safe for consumer consumption. Due to their shorter shelf life, bakery products are prone to food deterioration and spoilage issues. Therefore, chromatography techniques can also be used to detect adulterants and food safety issues in bakery products.

4.4. Food fraud detection in the confectionery industry

Recently, in the confectionery industry, advancements in the proliferation of processed foods incorporating high-intensity sweeteners as substitutes for sucrose and reduced salt have been observed. Neotame and Advantame, authorized as food additives serve as examples of these high-intensity sweeteners. A novel approach for concurrently detecting these two sweeteners in processed foods has been developed using LC coupled with mass spectrometry. This method meets all validation criteria boasting an LOQ of 0.01 μg/g across all samples (Iwakoshi et al., 2019). Melamine, a heterocyclic organic compound, can be deliberately mixed into powdered milk during chocolate milk processing to falsely raise its protein levels. However, melamine consumption poses serious health risks, including bladder, kidney stones, reproductive damage, and potentially even liver cancer. In the analysis of chocolates, solid phase extraction was employed, followed by HPLC to detect melamine. The LOD and LOQ for melamine were determined as 0.017–0.052 μg/mL (Abedini et al., 2021a). A study about Nabat, a traditional rock candy

popularly consumed in Iran, faces a concerning issue with the widespread use of synthetic food colors in unregulated sectors. Among the most frequently utilized colors are quinoline yellow and sunset yellow. In a study, five samples of Nabat were analyzed using HPTLC. Results revealed that artificial food colors were added to rock candy, with 26.53% of these dyes being banned substances. This highlights the critical need to monitor and regulate the use of synthetic dyes, especially in the production of Nabat (Sadeghi et al., 2020a).

Overall, the confectionary industry proved to be most appealing to consumers and it mostly targets children with its tasty products, including chocolate and chewing gums. However, there are chances for food fraud in such products, which can be detected using chromatography techniques. Further explained in Fig. 2 food fraud detection in different food items and chromatography potential in authentication method.

4.5. Other food categories

The researcher has explored the strategies implemented by companies within the Asia-Pacific honey supply chains to manage food fraud. The specific focus was on honey supply chains due to anecdotal evidence. It has been observed that food fraud is prevalent in honey supply chains because insiders often view it as a routine occurrence, sometimes even referring to it as "honey laundering." To address this issue, relevant food companies employed the Gioia method (a qualitative methodological approach designed to draft data analyses that can meet the rigorous standards of reliable research) (Hall, 2023). Similarly in another study HPLC-UV method was used to detect fraud in honey and to check its suitability when adulterated with samples like glucose and sugarcane syrups along with maple, corn, and rice syrups, a total of 155 honey samples belonging to different varieties were categorized with 100% classification and almost 30 types of sugar syrups were used. It was noted that this technique was effective in detecting adulteration up to 15% with minimum external and internal errors, HPLC-UV was used to detect the chemical profile of the samples, and chemometrics were used to further analyze it. This method proved helpful in detecting adulteration of sugar in honey that was most common and deceiving consumers at large scale (Egido et al., 2024). In another study related to honey, liquid chromatography coupled to isotope ratio mass spectrometry was used to check the authentication of honey and to access its quality, geographical origin, and botanical variety detected through NMR technology and LC-IRMS used to detect the addition of sugar varieties like C_4 and C_5 sugars. This technique was used to detect the glucose and fructose levels of the sugars to tackle the fraudulent activities in the honey through advances in chromatography (Biswas et al., 2023). Food fraud was caused by a lack of traceability in the supply chain and due to its complex market. The blending of honey with different sources was prevented by improving traceability along with this, evolutionary game theory was introduced to detect adulteration in Chinese honey, and local government penalties were implemented to prevent honey from adulteration and make it safe for consumers (Zhang et al., 2023). Several raw ingredients was at risk of fraud like potassium bromate (white crystal powder) is used as a "flour improver" in baking, but it is concerning due to its classification as a carcinogen and nephrotoxic substance. It is crucial to monitor bromate levels in flour products. Chromatography coupled with single quadrupole mass spectrometry is used for the detection of bromate in bread flour. The LOD and LOQ for bromate in the prepared solution are determined as 0.10–0.34 μg/L corresponding to 5–17 μg/kg in bread (Aggrawal & Rohrer, 2020). Likewise, nuts and seeds are commonlyknown as raw ingredient in many products and enjoyed as snacks or added to various dishes like salads, sausages, stews, or bakery items. Their regular consumption is associated with numerous health benefits for humans. Some nut-based products are at medium or high risk of fraudulent practices, including adulteration or substitution with cheaper, poor-quality ingredients while fraud in raw nuts was uncommon due to obvious visual distinctions. However, processed flours and pastes were more susceptible to fraud as their altered forms make detection more challenging. Researchers analyzed the metabolomic diversity of ten different types of nuts using non-targeted LC − HRMS. The study achieved an accuracy of 100% after validation from external sources (Campmajó et al., 2023). Another raw ingredient of baking industry is flavor that is widely used to provide specific flavors to food, vanilla is well-known as being used anciently in baking items but unfortunately, it is also not saved from food fraud and is replaced with a cheap synthetic process, its detection is not easy because it is added in very minute amount in items although a technique was designed to detect at low concentration. In the food products, the isotopic carbon ratio of the vanilla was determined through solid-phase extraction, the experiment was carried out on 23 samples and fraud was most likely carried out by the use of natural vanillin sourced from the vanilla pod which is the most expensive and scarce remains the most attractive and most common type of fraud that involves the use of synthetic vanillin, the cheapest and most easily accessible material. Results revealed that authentication of vanilla can be done easily through this approach and can be applicable on a large scale (Wilde et al., 2020).

5. Conclusion

The food sector's relatively lower profits compared to other industries often prompt producers to consider fraudulent practices. This unethical behavior is prevalent across various food types due to their high value and susceptibility to fraud. As a result, guaranteeing the genuineness of food items has become a pressing concern for producers, consumers, and policymakers. Addressing this issue requires the development of analytical methods capable of detecting fraudulent activities effectively. In this review, the methods utilized in detecting fraud, based on various chromatography techniques, are reviewed. These include LC, GC, HPLC, UPLC, TLC, ion chromatography, and affinity chromatography. Among them, HPLC is probably the most widely used, readily adaptable, and effective tool with the advantage of excellent resolution, sensitivity, and identification of a wide variety of compounds. All these types of chromatography proved helpful in industries as well as public health to save consumers from harmful outcomes. These Methds are especially effective when used in combination with other technologies i.e., HPTLC, and GC–MS. Moreover, chromatography-based techniques have applications not only in the dairy, meat, and cereal industry but it can also to be used in other food industries, including the beverage sector, Although chromatography techniques are effective for food fraud detection and authentication, the studies regarding their implementation for specific food products are limited. Chromatography also helped to tackle food fraud practically in 2008 in China to detect melamine in milk was a major cause of milk adulteration due to chromatography detection safety regulations of the country regulated, nowadays companies are tested with chromatography to answer their consumers whether their product is safe or not. Similarly, in South Africa, LC-MS was used to test 138 milk supplements and 64 were contaminated concluding that chromatography was used practically to combat food fraud cases. Despite the higher accuracy and sensitivity, the industrial applications of these techniques are limited due to the need for qualified and experienced personnel, maintenance and sampling costs, and time-consuming process. In the future, researchers can focus on the optimization of chromatography methods for specific food product authentication., Further studies are needed to overcome limitations and utilize chromatography at a commercial scale.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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Further-reading

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