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The crucial importance of soy sauce authenticity: Global trade, adulteration risks, and analytical challenges

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A R T I C L E I N F O

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A B S T R A C T

Background: Soy sauce, originating from China, has a long history in Asian countries. Recently, global production has markedly increased, and the consumer base is growing. The complex production process, involving various raw materials and multiple steps, poses multiple risks of fraud, some of which are related to food safety. Hence, soy sauce authentication is crucial.
Scope and approach: This review starts by investigating recent global production and trade volumes of soy sauce in major producing countries. It then outlines production standards and additive usage criteria in key countries. Building on this, it analyzes fraudulent activities observed in soy sauce over the past two decades. Finally, the review introduces principles, equipment, and data processing methods applied in analytical chemistry approaches for studying soy sauce authentication, considering both principles and applications.
Key findings and conclusions: In soy sauce production, soybean protein hydrolysis relies mainly on microbial fermentation, with an optional use of acid hydrolysis. The latter raises safety concerns, making fraudulent events in soy sauce production through these methods a significant concern. In recent years, soy sauce bottles have displayed various high-quality attribute labels, such as GM-free, organic, addictive-free, and handmade, etc. However, discerning the quality attributes in soy sauce through clear indicators is often very challenging. For the above issues, over the past decade or so, scientists have established a series of targeted and non-targeted analytical methods based on spectroscopy, mass spectrometry, and molecular biology techniques to verify the authenticity of soy sauce. Past research efforts are a good start, however, compared to other foods, the attention given to the authenticity analysis of soy sauce has not matched its importance. Future analytical approaches should focus on sample preparation, developing new rapid detection methods, and establishing chemical profile databases for diverse types of soy sauce. These efforts will further ensure the authenticity of soy sauce sold in many markets across the world.

1. An overview of soy sauce: introduction, production, and global trade scenario

1.1. Brief introduction about soy sauce

Soy sauce, originating in China over two thousand years ago, is a condiment containing umami compounds such as amino acids, peptides, and nucleotides (Diez-Simon et al., 2020). These compounds enhance the flavour of various food products, making soy sauce commonly used in cooking (Devanthi & Gkatzionis, 2019). Soy sauce is widely produced and consumed in Asian countries and indeed enjoyed globally. It is called "*jiàng yóu*" in China, "*shōyu*" in Japan, "*ganjang*" in Korea. The primary ingredients used in its production are soybeans and grains. The classic soy sauce is typically obtained through microbial fermentation,

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which occurs in two stages (Gao et al., 2023). In the initial stage, lasting several days, the steamed soybeans are mixed with roasted, ground wheat, and then inoculated with *Aspergillus oryzae*, a filamentous fungus. The starch and protein in the mixture breaks down under the action of *A. oryzae*. Following the first fermentation, brine or salt is introduced to bring about spontaneous fermentation, involving a diverse microbial community comprising various species of salt-tolerant bacteria, yeasts and fungi. The duration of this stage can vary from several months to a year, depending on the chosen processing method (Diez-Simon et al., 2020). In addition to the traditional fermentation method for producing soy sauce, some countries also permit alternative techniques, such as utilizing acid-hydrolyzed soybean proteins and employing dehydrated soy sauce to create liquid soy sauce.

1.2. *The production and global trade of soy sauce*

With its increasing popularity worldwide, the current annual production of soy sauce exceeds 10 million metric tons (Qian et al., 2023). China is the largest producers of soy sauce. Data from the National Bureau of Statistics of China shows the soy sauce production in China was 7.78 million tons in 2021 (J. Li, Dong, et al., 2022). Japan is another important soy sauce production country. According to the Ministry of Agriculture, Forestry, and Fisheries (MAFF), soy sauce production was about one million tons in 2020 (MAFF, 2022). To meet the consumption demands of the Western market, some Asian countries have relocated their soy sauce processing factories to Western countries such as the Netherlands and the United States. Consequently, an increasing number of countries worldwide have started exporting soy sauce. In recent years, the Netherlands and the United States have consistently ranked among the top five soy sauce exporting countries (Fig. 1). Although soy sauce is primarily consumed in Asian countries, it began to be sold and used globally after its introduction to Europe in the 17th century. Nowadays, thousands of tons of soy sauce enter the consumer markets of the countries such as United States, the United Kingdom, and Canada annually (Fig. 2).

Soy sauce has evolved from a traditional Asian condiment to a globally traded commodity, resulting in growing consumer concern for its quality and authenticity. Authenticity is especially crucial as it ensures consumer protection from fraud and purchasing counterfeit soy sauce. In addition, it also maintains supply chain transparency, ensuring food quality and safety. Therefore, the authenticity analysis of soy sauce is an important aspect of food integrity that requires attention. Addressing potential fraud issues and developing authenticity analysis methods are matters that cannot be overlooked.

2. Soy sauce standards and regulations in different countries

The official standards serve as the primary reference for soy sauce production (see Table 1). Asian soy sauce-producing countries such as China (SAC, 2018), Japan (MAFF, 2022ed), Singapore (SFA, 2022ed), and South Korea (MFDS, 2021b) have established clear definitions for soy sauce in their national standards and regulations, which aims to control aspects such as raw materials, processing methods, qualities, and the use of food additives. While the principles of soy sauce production are similar across Asian countries, there are a number of differences in these standards. In terms of raw materials, the primary ingredients specified by all countries are soybeans, grains, and salt. The Korean food code (MFDS, 2021b) regarding soy sauce also permits the use of proteins from other animal and plant sources. In Indonesia, the commonly used soy sauce is added with a significant amount of palm sugar (Sidharta, 2008).

The traditional production process of soy sauce relies solely on microbial fermentation. However, in order to shorten the production time, techniques involving acid hydrolysis or exogenous enzyme hydrolysis have also been employed in soy sauce production (Diez-Simon et al., 2020). Due to several safety incidents (Brereton et al., 2019; Lee & Khor, 2015), acid hydrolyzed soy sauce, also known as chemically hydrolyzed soy sauce, is considered a lower-quality product. In countries such as Japan, Korea and Singapore, there are clear standards for naming and differentiating soy sauce produced through microbial fermentation or through acid hydrolysis. Since 2018 in China, only products produced through fermentation are allowed to be labeled soy sauce as acid hydrolysis is no longer recognized as an accepted method to produce ‘genuine’ soy sauce (SAC, 2018). Food regulations in Malaysia also classify hydrolyzed plant protein seasonings separately from soy sauce (FSQD, 1985). In recent years, Western countries have also established standards for soy sauce production. For example, the U.S. Department of Agriculture has issued the Commercial Item Description (CID) A-A-20087D, which defines soy sauce production using both fermentation and non-fermentation methods (USDA, 2018).

Before being considered a commercial product, soy sauce may undergo additional processes that involve the addition of food additives, including caramel color, preservatives, flavor enhancers, sweeteners and more. In China, the types and amounts of food additives that can be added during soy sauce production must comply with the requirements of GB2760 (SAC, 2015). In Japan, adherence to the international food additive standard CODEX STAN 192 is mandated (CAC, 2021ed). In Singapore, Korea and Malaysia, adherence to the food additive regulations in the Food Regulation or Food Code for soy sauce is required.

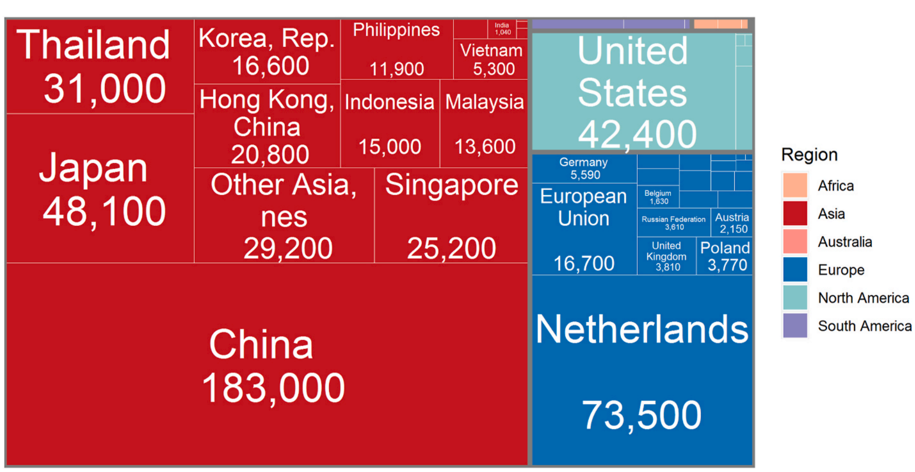

Fig. 1. The Major Soy Sauce Exporters and Export Volumes (Unit: Tons)
(The data is downloaded from the World Bank’s WITS database. The website address is: https://wits.worldbank.org/. The software used for data visualization is R and ‘ggplot2’ package.).

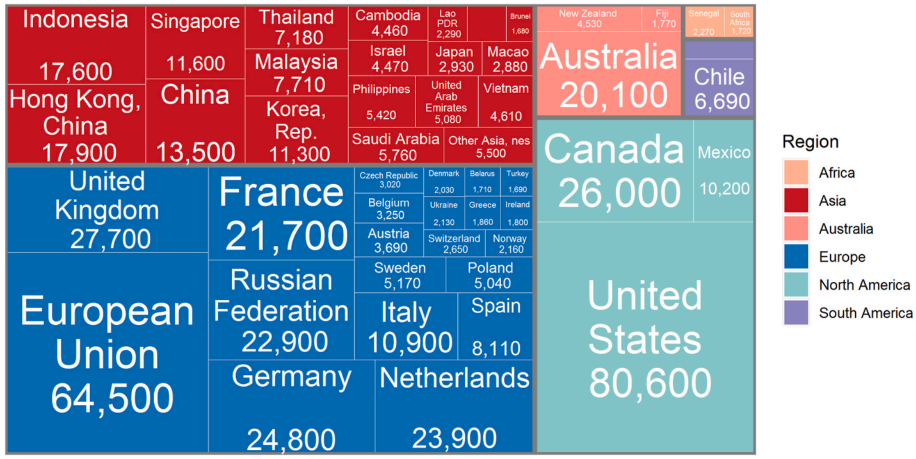

Fig. 2. The Major Soy Sauce Importers and Import Volumes (Unit: Tons)
(The data is downloaded from the World Bank's WITS database. The website address is: https://wits.worldbank.org/. The software used for data visualization is R and 'ggplot2' package.).

Table 1
The soy sauce standards in countries.

Countries	Definitions	Additives	References
China	GB 2717-2018	GB 2760	SAC, 2018, and 2015
Japan	JAS1703	CODEX STAN 192	MAFF, 2021; Codex Alimentarius Commission, 2021
Singapore	SFA. Food regulations	SFA. Food regulations	SFA, 2022
Korea	MFDS. Food code	MFDS. Food code	MFDS, 2021
Malaysia	FSQD. Food regulations	FSQD. Food regulations	FSQD, 1985
USA	CID A-A-20087D	GRAS	USDA, 2018; The FDA, 2023

3. Researchers' focus on soy sauce authenticity studies

The diversity of raw materials, complexity in production, and lengthy supply chains in soy sauce manufacturing create substantial opportunities for fraud, as illustrated in Fig. 3. Some research has been conducted to address potential fraud in soy sauce processing, including the development of methods for sampling and analyzing the products.

3.1. *Authenticity analysis of soy sauce production materials*

3.1.1. *Whole soybean vs. defatted soybean*

The main raw material for soy sauce production is whole soybeans (*Glycine max* L.) or defatted soybean meal. The price of defatted soybeans is 35% lower than that of whole soybeans, and in addition they ferment much more quickly (Tian et al., 2023). This results in a higher price for soy sauce made from whole soybeans as raw materials. From a chemical standpoint, whole soybeans contain typically 35–40% protein, 20% lipids, and other nutrients (Qin et al., 2022). In contrast, defatted soybean meals contain approximately 47% protein, 2% lipids, and other

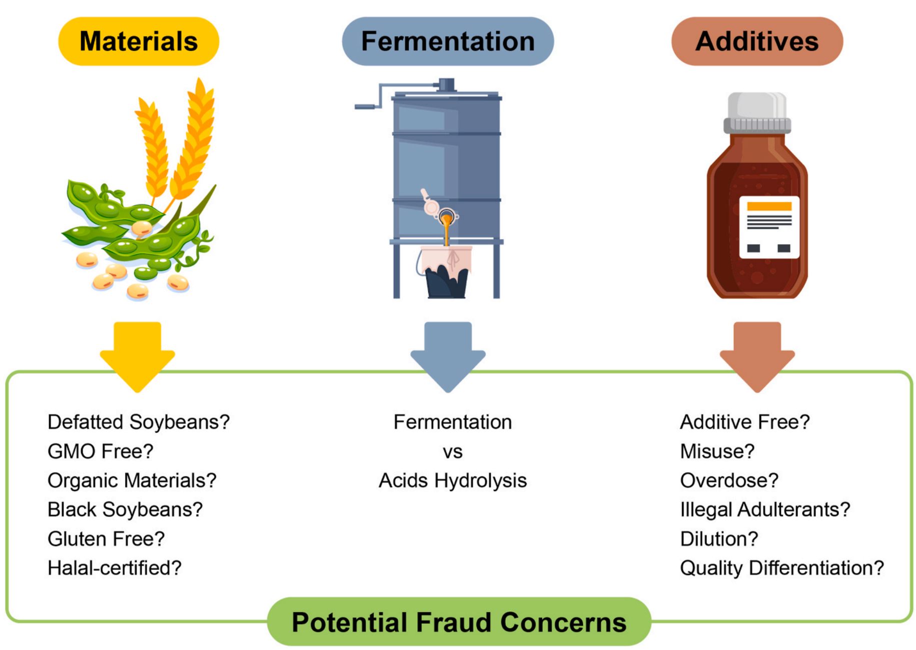

Fig. 3. Authenticity challenges in terms of soy sauce.

nutrients (García et al., 1997). The difference in chemical composition will impact the flavour and taste of the final soy sauce product. It was previously reported that soy sauce fermented with the former yields a milder taste, while the latter results in a stronger flavour (Kinoshita et al., 1998). However, other researchers have different interpretations of data generated by sensory evaluation, they described that soy sauce produced by defatted soybeans has stronger cooked potato-like and acids notes, and lower smoky, caramel-like and malty notes (Jeong et al., 2004; Tian et al., 2023). For quality inspectors and consumers, distinguishing between these two soy sauces is not that straightforward based on these sensory descriptions. Researchers have developed various identification methods to collect global chemical profiles of soy sauce made from defatted and whole soybeans for classification, as presented in Table 2 (Iizuka & Aishima, 1999; Kinoshita et al., 1998).

3.1.2. High-quality labels: GMO-free, organic, and more

Commercial cultivation of genetically modified (GM) soybean varieties commenced in 1996, quickly becoming the predominant soy crop in major producing countries (Nikolić et al., 2014). Nowadays, more than 80% of soybean varieties are GM (Voora et al., 2020). The primary soy sauce exporting and importing nations show notable disparities in their attitude towards GM foods, ranging from outright prohibition to frameworks that treat both conventional and GM products similarly (Turnbull et al., 2021). In addition, GM organisms in crops represent a significant opportunity in the field of food fraud i.e. false claims of non-GM on products. Therefore, the identification of authentic and fake soy sauce labeled as non-GM is an important research focus. Considering the widespread cultivation and usage of GM soybeans globally, the differences between genes and metabolites have been utilized to identify the presence of GM soybean components in food (Hrbek et al., 2017; Turkec et al., 2016).

Apart from the GMO-free label, organic certification is another widely employed designation for soy sauce. In recent years, false organic labeling has been a growing issue in food fraud incidents, soybeans play a crucial role in cases of fraud, where products are mislabeled as organic instead of non-organic (Giannakas & Yiannaka, 2023). Furthermore, the definitions and certification standards for organic products can differ quite widely from one country to another (Giannakas & Yiannaka, 2023). In addition to GM-free and organic labels, researchers have also developed several techniques to examine the authenticity of sauces labeled as gluten-free (Li et al., 2018), halal (Mahama et al., 2020), or made with the more expensive black soybean (Wang et al., 2023). Generally, it is difficult to ascertain the authenticity of these attributes listed on product labels solely through sensory evaluation. This poses a major challenge for consumers to discern the genuine quality of soy sauce in terms of the price they pay for products. Consequently, industry and government regulators should take more action to ensure the credibility of claims made about these attributes.

3.2. Authenticity assessment of protein hydrolysis methods in soy sauce

3.2.1. Months-long fermentation vs. hours-long acid hydrolysis

Traditional soy sauce requires months or even a year of fermentation by microorganisms, making it a lengthy and costly processing method. In contrast, a portion of soy sauce is produced using acid-hydrolyzed vegetable proteins (acid-HVPs). In the past, public concern was raised when certain soy sauce samples containing acid-HVPs were found to contain high levels of 3-monochloropropane-1,2-diol (3-MCPD), which is considered to be genotoxic and carcinogenic (Syed Putra et al., 2023; Wong et al., 2020). Over the past two decades, most of the bans and recalls in soy sauce trading have been due to the discovery of high levels of MCPD in the products (Dolan et al., 2010; Wong et al., 2020). Therefore, this is the most concerning research topic with regards to soy sauce safety.

In addition to safety concerns, the acid hydrolysis method for soy sauce production is generally regarded as lower in quality due to its less

Table 2
Analytical methods used for determination of soy sauce authenticity.

Category	Sub-category	Analysis Technique[a]	Data mining methods[b]	References
Materials	Organic and non-organic soybeans	NMR	OPLS-DA	Kamal et al. (2022)
Materials	GM-free soybeans	PCR	–	Arun et al. (2013)
Materials	Whole and defatted soybeans	MIR, NIR	LDA using genetic algorithms	Iizuka et al. (1999)
Materials	Whole and defatted soybeans	HPLC	Pattern recognition analysis	Kinoshita et al. (1998)
Production methods	Fermentation and acid hydrolysis	Fluorescent probe	Quantification via standards	Zhang et al. (2018)
Production methods	Fermentation and acid hydrolysis	NMR	ML and classification	Greer et al. (2018)
Production methods	Fermentation and acid hydrolysis	FRET	Quantification via standards	Gao et al. (2015)
Production methods	Fermentation and acid hydrolysis	LC	Quantification via standards	Zhu et al. (2010)
Production methods	Fermentation and acid hydrolysis	LC-MS	Quantification via standards	Sano et al. (2007)
Production methods	Brine adulteration	Vis-NIR	PLS-DA	Chen, Hou, et al. (2023)
Production methods	Brine adulteration	Vis-NIR	SNV-PLS-DA	Fu et al. (2022)
Production methods	Brine adulteration	FT-NIR	PLS	Natcha et al. (2014)
Finally products	Different brands	Vis-NIR	kNN	Chen et al. (2022)
Finally products	Halal-certified labels	GC	Quantification via internal standards	Mahama et al. (2020)
Finally products	Different brands	Glassy carbon electrode	CA	Wu et al. (2020)
Finally products	Different brands	NIR	PCA, LDA, PLSR	Rosales et al. (2019)
Finally products	Different brands/quality	Vis-NIR	Full-SVM, PSO-SVM	Hu et al. (2019)
Finally products	Different brands	Tri-Step IR, E-nose	PLS	Zhu et al. (2018)
Finally products	Different quality	CE	PCA	Luo et al. (2017)
Finally products	Excessive additive usage	NMR	Quantification via standards	Ohtsuki et al. (2015)
Finally products	Different quality	LC-MS	Quantification via standards	Kuroda et al. (2013)
Finally products	Excessive additive usage	NMR	Quantification via standards	Ohtsuki et al. (2012)
Finally products	Different brands	E-tongue	PCA, BP-ANN	Ou-Yang et al. (2011)
Finally products	Different quality	LC, NMR	Pattern recognition analysis	Kinoshita et al. (1997)
Materials/ Finally products	Soybeans and black beans/ Different Origins	GC-MS	PCA, OPLS-DA	Wang et al. (2023)
Production methods/	Different brands/ geography/	FAIMS	PCA	Jin et al. (2022)

(continued on next page)

Table 2 (*continued*)

Category	Sub-category	Analysis Technique[a]	Data mining methods[b]	References
Finally products	production processes			
Production methods/ Finally products	Different brands/ geography/ production processes	Nine physico-chemical properties	CA, PCA, DPLS, LDA, kNN	Chen et al. (2010)

[a] Abbreviations for some analysis technique: Fluorescence resonance energy transfer (FRET), Capillary electrophoresis (CE), and High-field asymmetric waveform ion mobility spectrometry (FAIMS).

[b] Abbreviations for data mining methods: Orthogonal partial least squares (OPLS), Discriminant analysis (DA), Linear discriminant analysis (LDA), Machine learning (ML), Partial least squares-discriminant snalysis (PLS-DA), Standard normal variate (SNV), k-Nearest neighbors (kNN), Cluster analysis (CA), Principal component analysis (PCA), Partial least squares regression (PLSR), Support vector machine (SVM), Particle swarm optimization algorithm (PSO), Backpropagation artificial neural network (BP-ANN), and Discriminant partial least squares (DPLS).

appealing aroma and flavour (Luh, 1995). Hence, researchers have developed methods to analyze the differences between soy sauce produced using the two production methods. (Gao et al., 2015; Sano et al., 2007; Tan et al., 2015; Zhang et al., 2018; Y. Zhu et al., 2010). Acid treatment process leads to the formation of distinct decomposition products, such as 3-MCPD (Lee & Khor, 2015; Tang et al., 2023; Wong et al., 2020) or levulinic acid (Sano et al., 2007), which are unique and differ from those generated during microbial fermentation. Moreover, during acid hydrolysis process, the majority of tryptophan is broken down. Therefore, researchers have developed analytical methods based on this to conduct authenticity testing for both types of soy sauce (Zhang et al., 2018; Zhu et al., 2010).

3.2.2. *Exogenous enzymatic hydrolysis: Friend or Foe?*

Given the lengthy fermentation process traditionally used for soy sauce production, researchers are developing methods that involve the addition of exogenous enzymes such as proteases (Chen, Hou, et al., 2023) and lipases (Xiang et al., 2019), to accelerate the fermentation process. These aim to enhance hydrolysis efficiency while also improving the quality of the soy sauce. It also should be noted that a study has found that the additional addition of lipase may promote the generation of 3-MCPD in soy sauce production (Xiang et al., 2019). The high cost of enzyme preparations and the potential benefits of shortening the production cycle or enhancing soy sauce quality will be a determining factor in whether this method will be widely adopted in industrial soy sauce production in the future.

3.3. *Authenticity concerns on the finished soy sauce products*

3.3.1. *Legal additives vs. illegal adulterants*

Although consumers tend to prefer 'additive-free' or 'free-from' soy sauce, there are many additives that can be used in soy sauce that comply with food standards. These include colour enhancers (such as caramel colour and brown sugar), flavor enhancers (such as sodium glutamate, 5′-disodium flavorful nucleotide, sugar, and yeast extract), preservatives (like potassium sorbate and sodium benzoate), and acid regulators (such as lactic acid and spirit vinegar) among others. Additionally, some soy sauces are derived from dehydrated soy sauce. In the dehydration process for soy sauce in powdered form, drying carriers like crystalline carbohydrates may be employed, particularly when utilizing methods such as spray drying (Wang & Zhou, 2015). While food additives may enhance the quality of soy sauce, researchers are concerned about their overuse and the subsequent safety risks (Ohtsuki, et al., 2012, 2015; Song et al., 2019). For example, excessive use of benzoic acid may lead to metabolic acidosis and allergic reactions (Ohtsuki et al., 2012). Another additive worth noting is caramel colour, brown liquid or powder, frequently used in dark soy sauce. It is important to be aware that certain types of caramel colors may contain 4-methylimidazole (4-MEI), which is a health concern (Jacobs et al., 2018). In general, legally added additives in soy sauce considered safe within existing regulatory limits. However, the types and quantities used are crucial aspects that cannot be overlooked in authenticity analysis to avoid the improper use of additives.

3.3.2. *Counterfeiting of A-brands soy sauce*

Aside from improper use of additives, the most serious issue in soy sauce counterfeiting is substituting or diluting fermented A-brand soy sauce with chemically blended alternatives such as brine, amino acids and caramel colouring (Chen, Hou, et al., 2023; Greer et al., 2018; Natcha & Panmanas, 2014). This counterfeit soy sauce can have significant negative impacts on human health, which is a primary concern for regulatory authorities (Taipei Taibei Times, 2005; Punch, 2023; Caixin, 2017). In this area of research, due to the temporary absence of specific chemical or biological targets, researchers have developed spectroscopic and sensory array analysis methods to study the chemical fingerprints of soy sauce from different brands, grades, qualities, and origins for classification and differentiation (Chen, et al., 2022, 2023; Hu et al., 2019; Jin et al., 2022; Natcha & Panmanas, 2014; Ohtsuki et al., 2015; Zhu et al., 2018).

4. Analytical methods and data processing strategies in soy sauce authenticity analysis

From the previous sections it can be observed that there are various types of fraud activities that may occur during the soy sauce production process. However, compared to many other topics in authenticity analysis studies of food, the quantity is much lower, with an average of only 2–3 publications per year (Fig. 4). This section will now introduce analytical methods used for determination of soy sauce authenticity, as summarized in Table 2, based on publications over the past two decades.

Choosing the appropriate authenticity analysis method is crucial, which requires consideration of the type of soy sauce fraud, the applicability of chemical analysis and the data interpretation methods. Historically, researchers primarily focus on identifying whether soy sauce has been manufactured by means of acid hydrolysis or other procedures (Fig. 5). Since the chemical nature of acid hydrolysis and microbial community hydrolysis differs significantly, acid-hydrolyzed soy sauce provides some clear selectable chemical targets, such as 3-MCPD (Syed Putra et al., 2023). This specific compound-targeted authentication technique is referred to as targeted methods, involves relatively mature chemical analysis and data processing methods, where the content of indicators in soy sauce samples is determined by comparing them with standard, well characterised samples.

While in recent years, an increasing number of high-quality labels have appeared on soy sauce bottles, and it is often difficult to differentiate the raw materials, fermentation periods, and other quality attributes that form part of the labeled in soy sauce through clear indicators. Traditional targeted analysis is unlikely to uncover adulterated samples when the type of fraud is unknown. Therefore, advanced non-targeted analytical chemistry methods, such as profiling and fingerprinting accompanied by multivariate statistics (chemometrics), are becoming crucial in the authenticity analysis of soy sauce (Rodionova & Pomerantsev, 2020), as illustrated in Fig. 5. The chemometric methods to interpret non-targeted analytical chemistry methods can be categorized into unsupervised and supervised approaches (Biancolillo et al., 2020). The former is used to conduct clustering analysis to identify differences between various soy sauce samples (Chen, Hou, et al., 2023; Jin et al., 2022; Wang et al., 2023), while the latter utilizes analytical data from known soy sauce samples to create a training set and build a classification model for categorizing unknown soy sauce samples (Hu et al., 2019; Ou-Yang et al., 2011; Rosales et al., 2019; Wang et al., 2023).

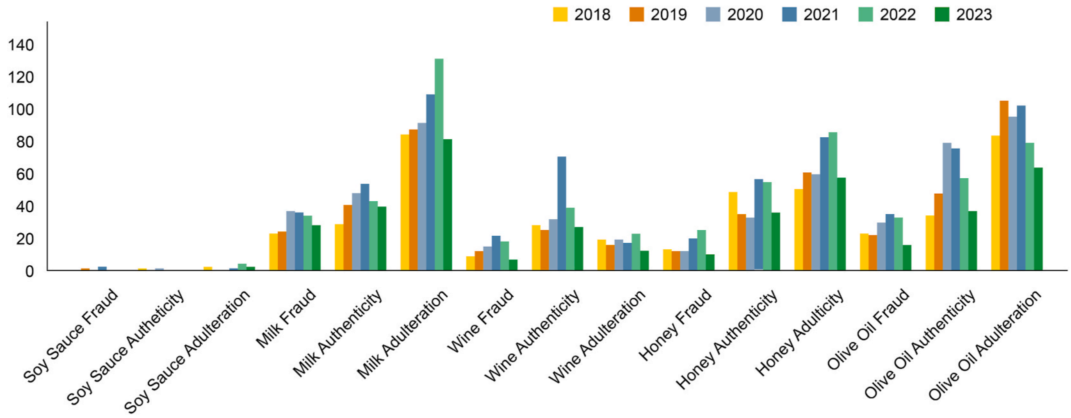

Fig. 4. The number of recent authenticity analysis publications on a range of foods (retrieved from Web of Science).

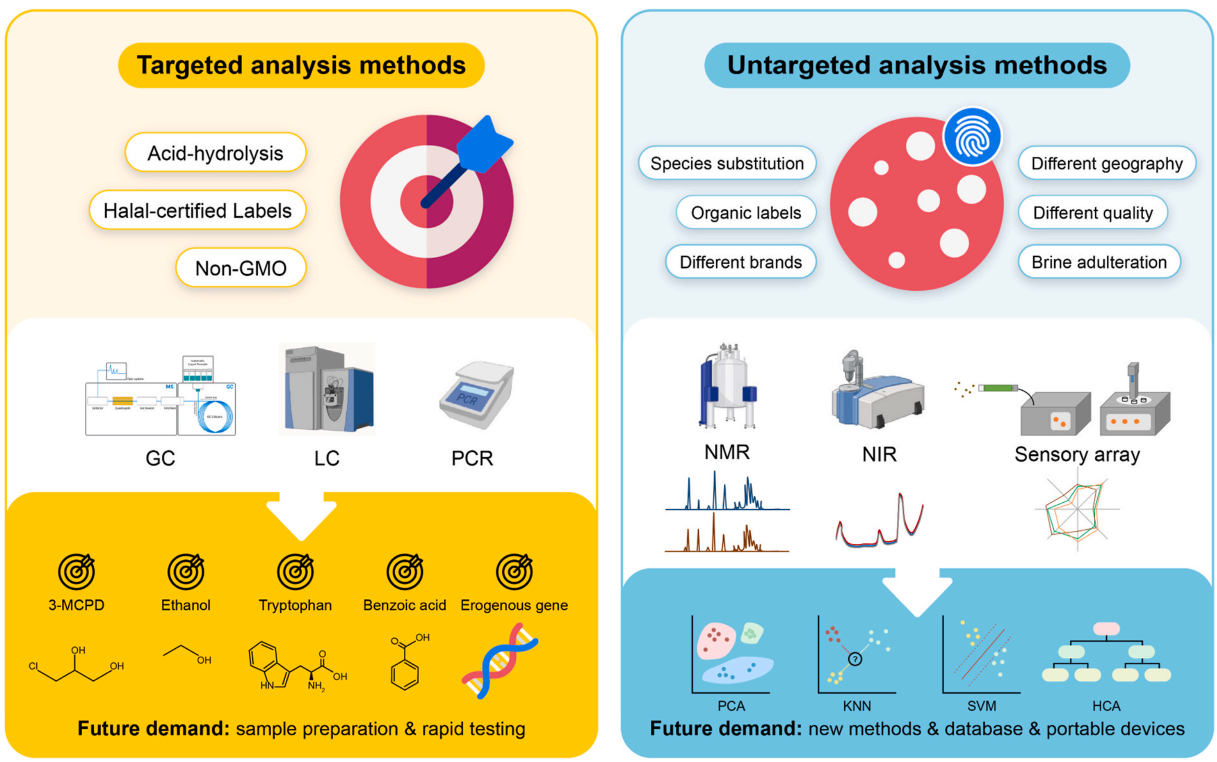

Fig. 5. Types, applications, and future needs of soy sauce authenticity analysis methods.

4.1. Spectroscopic methods

Spectroscopic methods, such as ultraviolet (UV) spectroscopy, visible (Vis) spectroscopy, infrared (IR) spectroscopy, nuclear magnetic resonance (NMR), and Raman spectroscopy, are ideal for quickly screening food authenticity. These techniques are favored because they require minimal sample preparation, are low-cost, and are ease to use (Müller-Maatsch et al., 2021). Currently, researchers have developed authenticity analysis techniques for soy sauce based on IR and NMR spectroscopy, employing both targeted and non-targeted approaches. Although Raman spectroscopy is also a commonly used technique for food authenticity, such as in edible oils, beverages, and honey (Xu et al., 2020), there have been no reported studies on soy sauce authenticity using this method.

4.1.1. Vis-NIR spectroscopy

Among the various spectroscopic methods, visible and near-infrared (NIR) spectroscopy (wavelength: 400–2500 nm) stands out as the most commonly employed technique in the analysis of soy sauce authenticity. It allows for rapid and simultaneous qualitative as well as quantitative analysis. Different wavelengths were necessary for differentiation, reflecting variances in carbon-hydrogen bonds, carbonyl groups, and triple bonds among the samples. In NIR-based targeted analysis, amino nitrogen served as the primary indicator for assessing the quality of soy sauce (Hu et al., 2019; Ou-Yang et al., 2013; L. Zhu et al., 2018). Additionally, salinity, total acidity, and color ratio measurements can also be employed as analytical parameters (Hu et al., 2019). More recently, it has been predominantly employed in non-targeted NIR methods to distinguish between different brands and qualities, as well as to identify brine adulteration in soy sauce (Chen, et al., 2022, 2023; Fu et al., 2022; Rosales et al., 2019; Zhu et al., 2018). In investigating the authenticity of soy sauce using non-targeted NIR methods, researchers primarily concentrate on the data analysis that follows the collection of NIR spectra. Variables are critical to the prediction performance of the model in NIR spectroscopy analysis (Yun et al., 2019). Specifically, in the soy sauce Vis-NIR spectroscopy analysis, variable selection and discriminant analysis (DA) are mainly performed using partial least squares (PLS) methods. These studies, which involved sample sizes ranging from several dozen to several hundred, demonstrated that PLS-DA is highly effective in distinguishing between different types of soy sauce.

In addition to classical chemometric models like PLS, artificial intelligence methods, particularly deep learning (DL), have shown significant predictive power on large datasets and in handling complexities response variables (Mishra et al., 2022). However, the soy sauce dataset size, crucial for the predictive accuracy of DL models, is far from optimal due to a lack of sufficient and standardized spectral databases. This scarcity makes it challenging to introduce new algorithms and transfer models across different equipment (Hebling e Tavares et al., 2022). Consequently, the findings from individual studies are often not effectively utilized by others in the field. Establishing a comprehensive soy sauce database and facilitating the sharing and mutual use of spectroscopic information from diverse data sources are current topics of considerable discussion.

In recent years, the development of portable and miniaturized infrared devices has been a focus point in this field (Müller-Maatsch et al., 2021). While many databases have been produced based on non-portable NIR instruments (Beć et al., 2022), there are a small number of successful cases of spectral transfer to handheld devices, particularly in applications such as meat analysis (Kademi et al., 2019). With the continued interest in soy sauce authenticity analysis, researchers can hope for a time when a data-rich spectral database will be available allowing for a simple, rapid and low cost measurement to assess the quality and authenticity of soy sauce.

4.1.2. NMR spectroscopy

Both NIR and NMR are non-destructive testing techniques. NIR is suitable for analyzing the macroscopic composition and relative content of samples. On the other hand, NMR offers in-depth chemical information, including details about the types of nuclei present, the chemical environment, and the connectivity between different atoms in a molecule (Sobolev et al., 2019). Consequently, NMR is adept at detecting molecular structures. Moreover, the NMR phenomenon can be directly transferable from benchtop instrumentation to high field setups (Sobolev et al., 2019). Several studies utilized NMR to quantitatively analyze targeted compounds in soy sauce, aiming to prevent the overuse of additives and ensure the quality of the end product (Kinoshita et al., 1997; Ohtsuki, et al., 2012, 2015). NMR has also been utilized in non-targeted authenticity analysis of soy sauce. Researchers have either differentiated soy sauce samples by combining spectra with chemometric methods (Greer et al., 2018) or explored differences between organic and non-organic soy sauce through NMR-based metabolomics analysis (Kamal et al., 2022). Compared to other foods that receive much more attention from scientists researching food authenticity, there are very few NMR spectra databases available for authentic soy sauce samples. The previously mentioned research reports typically involve only a few to a dozen soy sauce samples, and a standardized commercial database has not been established yet. While in food authenticity analysis, NMR is a fast-growing analytical techniques in non-targeted analysis, widely applied in the analysis of samples such as wine (Solovyev et al., 2021), honey (Vit et al., 2023), fruit juice (Herbert-Pucheta et al., 2021), and olive oil (Maestrello et al., 2022). NMR manufacturing companies have built reference databases for the aforementioned food items, with the quantity of sample data reaching up to tens of thousands. Compared to the aforementioned items, there is still significant room for development in both the development of NMR analysis methods and the collection of NMR spectra for authentic soy sauce samples.

4.2. Mass spectrometry analysis

The mass spectrometer is acknowledged to be an excellent detection device due to its high sensitivity, accuracy, and resolution (Suman et al., 2021). Capable of providing both qualitative and quantitative information, it demonstrates versatility over a wide range of applications in targeted and non-targeted food authenticity testing (Dou et al., 2023). During the fermentation process of soy sauce, the microbial community degrades proteins, sugars, lipids, and other compounds, generating both volatile and non-volatile metabolites. These substrates and products can be analyzed using different forms of mass spectrometry. From the perspective of equipment selection, the analyzable components in soy sauce can be classified into volatile organic compounds (VOCs) and liquid-phase components in the brown liquid. VOCs primarily consist of acids, alcohols, aldehydes, esters, and more (Diez-Simon et al., 2020), which can be effectively identified by GC-MS, a field also referred to as volatile metabolomics. In the liquid phase, proteins, peptides, amino acids, organic acids, and lipids can be analyzed by various types of LC-MS methods.

Due to the low detection limits of mass spectrometry, it has been applied in the analysis and detection of trace fraud markers such as levulinic acid (Sano et al., 2007) and 3-MCPD (Genualdi et al., 2017) in soy sauce. In addition to these target analysis applications, the sensitivity of the methodology allows for the rapid acquisition of a large volume of fingerprint data from samples with a relatively high throughput. Consequently, compared with other non-targeted analytical chemistry methods, MS-based detection techniques stand out as the most powerful tools for differentiating between genuine and adulterated food and identifying new markers of fraudulent practices. For example, a study found that the primary VOCs in fermented soy sauce are alcohols and esters, whereas in acid-hydrolyzed soy sauces, they are present as heterocyclic compounds (Lee et al., 2006). More recently, a GC-MS based method has been utilized to identify soy sauce adulteration with different bean species and origins (Wang et al., 2023). This study identified 49 features for distinguishing bean types in soy sauce and 16 features for the differentiating the geographical origins of soy sauce.

While there have been a very limited number of reports on the analysis of VOCs in soy sauce for food authenticity analysis, they have been extensively studied and discussed in the field of fermented foods research. Numerous studies concentrated on differentiating soy sauce fermented by various starter cultures (Wang et al., 2024; Zhang et al., 2023), during different fermentation periods (Feng et al., 2014), and using different raw materials (Liang et al., 2019), based on VOC profiles. Although the applications may be for different purposes, these studies essentially align with the objectives of food authenticity analysis. Unlike spectroscopy, detection methods based on MS require sample pretreatment and the optimization of analytical workflows. The choice of methods for the extraction and enrichment of VOCs, the selectivity of the GC chromatographic column, the use of GC × GC two-dimensional analysis schemes, and the selection of MS detectors can significantly impact the types of compounds detected, the resolution and detection limits achieved. Therefore, it is necessary to predict the most appropriate analysis methods based on the potential differences in chemical properties among samples before conducting authenticity analysis of soy sauce.

Apart from volatile metabolomics, the use of non-target metabolomics or peptidomic analysis techniques based on LC-MS has rapidly developed in food authenticity analysis (Zhong et al., 2022). Given that soy sauce comprises key components in the form of protein hydrolysates and contains many peptides with a molecular weight exceeding 10 kDa (Nikkuni et al., 1984), comprehensive development and application of strategies employing peptidomic approaches to authenticate soy sauce are an attractive option for future research. For example, as many food allergens are proteins, these methods have the advantage of aiding in the identification of the authenticity of claims such as "gluten-free" or "allergen-free" for soy sauce (Li et al., 2018). Although belonging to different research fields, researchers in the field of fermented foods have extensively utilized this method to investigate the metabolomics differences among various types of soy sauces, particularly differences in taste modulating peptides (Jünger et al., 2022; Shiga et al., 2014; Yamamoto et al., 2014). The research protocols and findings in this area can serve as valuable references for scientists studying soy sauce authenticity via LC-MS based protocols. To identify robust methodologies to verify organic certification and geographical origin claims make the authenticity analysis of soy sauce challenging. MS-based analytical methods, such as metabolomics, lipidomics, peptidomics, and proteomics techniques, have been effectively utilized in the geographical origins, species identification and allergens analysis. The selection of the method is closely tied to the chemical composition of the food. For example, lipidomics is used to study the authenticity of salmon, while proteomics and peptidomics are employed to investigate the authenticity of milk, meat, and fish (Hong et al., 2023; Valletta et al., 2021). Without a doubt, MS-based methods have high potential for accurately distinguishing subtle differences among soy sauce samples. However, its full potential is not yet realized in the authenticity analysis of soy sauce due to two main challenges: first, the high concentration of salts can interfere with sample processing and analysis (Li, Dong, et al., 2022); second, most existing methods are suited for analyzing non-polar compounds, whereas soy sauce contains numerous polar compounds (Lioupi et al., 2023). Therefore, mature sample preparation and analysis methods specifically tailored for soy sauce still require optimization. This includes the development of suitable methods for metabolites and peptide enrichment, desalination, as well as the customization of UPLC or nano-LC separation techniques specifically designed for soy sauce samples.

4.3. DNA analysis

DNA analysis technologies are the most effective methods for identifying a certain species and determining GM components in food and includes various techniques such as quantitative PCR (qPCR), restriction fragment length polymorphism (RFLP), and next-generation sequencing (NGS) (Böhme et al., 2019). Currently, the main targets used for analyzing GM-free and GM soybeans in food are the endogenous gene *lectin* and the exogenous gene *CP4-epsps* (Tian et al., 2014). However, the degradation of target genes in different soybean processed products is significantly influenced by the processing methods (Chen et al., 2007). For soy sauce, extracting a sufficient amount of DNA from the final product is highly challenging (Özgen Arun et al., 2013) and high-quality enrichment of target DNA fragments from soy sauce is a prerequisite for authenticating DNA technology (Singh et al., 2021).

4.4. Sensor array analysis

Sensor array analysis has the capability to detect and respond to changes in the concentration of specific chemical compounds in both liquid and gas samples. Researchers employed electronic electrodes or sensors within sensor array analysis to gather output signals from soy sauce liquid and volatile samples, facilitating the profiling analysis of various types of soy sauce (Ou-Yang et al., 2011). They subsequently differentiated those profiles using various statistical methods. Therefore, sensor array analysis can also be utilized for authenticating soy sauce.

5. Future outlook

Over the past two decades, scientists have made significant efforts to address soy sauce fraud. These noteworthy achievements do not signify the completion of soy sauce authenticity analysis. There is still a lot of work to be done in future analysis methods. Firstly, the quantity of chemical profiling and fingerprint databases for soy sauce is still far from optimal. It is essential to consider that there are numerous factors affecting the chemical composition of soy sauce, i.e. an example of a highly complex food matrix. Apart from information reflected on labels such as salt content, raw materials, and hydrolysis process, many factors such as types of starter cultures and fermentation conditions, can also have an impact. In the future research on soy sauce authentication, it is essential to collect a large library of samples with sufficient metadata that will influence the chemical composition of soy sauce to allow robust and fit for purpose analytical techniques to be developed and validated. Achieving this goal necessitates strong collaboration between scientists and the industry.

Secondly, authenticity analysis of soy sauce through spectroscopic measurements is marked by its simplicity of operation and sample pretreatment. The collection and creation of the spectroscopic database for soy sauce, along with data transfer between devices, will prove crucial. Furthermore, the future advancement of miniaturization, portability, and cost-effectiveness in analytical devices will aid in advancing rapid detection of fraud and broadening its practical applications to real-world situations. In addition, exploring the development of new analytical approaches for soy sauce authenticity analysis will offer insights and improvements. For example, the authenticity analysis method for soy sauce based on Raman spectroscopy needs to be explored. Additionally, powerful MS-based techniques such as metabolomics and proteomics analysis methods need to be fully developed to play a greater role in soy sauce authenticity analysis.

6. Conclusions

In this study, we have revealed that from raw materials to the finished product, soy sauce undergoes numerous production stages, making it highly susceptible to various types of fraudulent activities. Consequently, it is crucial to differentiate the chemical composition variances among different soy sauces to address a broad range of issues some of which are directly related to food safety. Research over the past decade has laid a good foundation for soy sauce authenticity analysis. Building upon this foundation, improving existing methods and developing new authentication techniques tailored to soy sauce can ensure that every consumer purchases authentic and safe products. This, in turn, will foster the healthy development of the soy sauce industry and ensure consumer trust in the products so widely used globally.

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

No data was used for the research described in the article.

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