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PROOF
REVIEW

AQUATIC FOOD STUDIES

Application of Spectroscopic-Based Techniques in Seafood Authentication

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Abstract

The availability and sale of seafood have grown significantly over the past few decades, and there is the possibility of marketing fraudulent fish and fishery products. Seafood fraud is a global concern, affecting the conservation of marine resources and leading to significant drops in consumer confidence. Additionally, it complicates marine conservation planning and poses potential public health risks. As a result, ensuring the safety and authenticity of seafood is crucial. As it stands, determining the safety and authenticity of seafood has grown to be a big problem. There is, therefore, a need to authenticate seafood along the value chain to ensure food safety. Spectroscopy-based techniques or approaches have been routinely used to identify and stop seafood fraud. As a result, the goal of this study is to provide the most recent information on the use of spectroscopy-based approaches for seafood species authentication. This review provides important information on spectroscopy-based techniques applied to authenticate seafood. This review reveals that seafood can be authenticated using near-infrared, mid-infrared, Raman, ultraviolet-visible, and nuclear magnetic resonance. The complexity of the sample matrices, variations in the sample properties, spectral interferences, need for calibration models, requirements for specialized equipment, limited spectral range, expertise in data analysis, and limited sensitivity are the challenges and limitations of spectroscopy in seafood authentication. Going forward, there is a need to integrate multiple techniques, develop portable instruments, and apply big data and machine learning.

1. Introduction

As a safe and nutritious food source, seafood has recently drawn interest on a global scale (Kang, 2021). Polyunsaturated fatty acids (PUFAs), which are known to influence prostaglandin synthesis and, therefore, promote wound healing, are among the necessary fatty acids found in fish which are a rich source of them (Kryzhanovskii et al., 2009; Zhang et al., 2010; Kindong et al., 2017). For proper human growth and healthy functioning, seafood must have essential proteins, fatty acids, and micronutrients (Cubillo et al., 2023). As a result of its health benefits, seafood is a crucial component of a healthy diet (Castro et al., 2023). There has been an increase in consumer demand for fish and fishery products over recent decades due to their nutritional properties (Alamprese & Casiraghi, 2015). This phenomenon has given rise to an increase in seafood fraud, which refers to the use of sub-par materials or components, or the removal of essential nutrients, is undoubtedly a common activity in the food industry (Chaudhary et al., 2018). According to estimates, food fraud costs the global food business USD 10–15 billion annually. In commercial marketplaces,

seafood fraud is thought to be more widespread than ever before (Abdullah & Rehbein, 2014). According to Hassoun et al. (2020), the mislabelling of provenance (geographical or botanical origin), species substitution, differences in the farming or breading technique, the addition of non-declared substances, and fraudulent treatments and the non-declaration of processes, such as prior freezing, irradiation, and microwave heating, are just a few examples of the many ways that fraud in animal origin products including seafood can manifest itself (Figure 1). This can be attributed to the industry's increasing competitiveness and the diversification of the fish supply chain, which has resulted in a vast array of products with similar looks but very differing global quality features being available on the global market (Ghidini et al., 2019).

Consumers, traders, producers, and industry players are very concerned about the authenticity of fish and seafood (Grassi et al., 2018). To ensure public health, the most basic criteria are food quality and safety. Seafood must be authenticated and tracked along the supply chain to combat seafood fraud (O'Brien et al., 2013). However, it is difficult to trace seafood fraud due to the uncontrolled and complicated "boat-to-plate" supply chain. Seafood authentication is important for several reasons. Firstly, it is important because related seafood species have a large number of phenotypic similarities; therefore, there may be purposeful or accidental adulteration, such as substituting similar high-value species with low-value species or passing off aquatic items as wild fishing (Pazartzi et al., 2019; Xu et al., 2020). The most common supply chain fraud involving fish and fish products include selling frozen or thawed products as fresh fish and switching out pricey species for less priced ones (Alamprese & Casiraghi, 2015). In addition to this, the weight of seafood and its products may be purposefully increased along the value chain, making seafood authentication important (Moore et al., 2012).

A food product is authenticated by being checked to see if it adheres to regulations and matches the claims on the label (Chaudhary et al., 2018). Consuming tainted or falsified seafood might result in major health issues like allergies and infections (Dawan & Ahn, 2022).

Food authentication methods are intended to identify between original and counterfeit goods, eliminate unfair competition in the market, and protect consumers from fraud (Chaudhary et al., 2018). Several methods have been applied to the authentication of seafood. These include spectroscopic-based techniques, DNA/molecular-based methods, and protein-based chemical and chromatographic techniques. These spectroscopy-based techniques are important because of their ability to accurately identify the composition and properties of seafood based on its distinctive spectral signature, which can be used to distinguish between species and identify any fraudulent activities like species substitution or adulteration. They are non-destructive and can provide high accuracy in terms of results.

Given the above, the purpose of this review is to shed light on the application of spectroscopic-based techniques in the authentication of seafood. Primarily, the review aims to bring together updated knowledge on some spectroscopic-based techniques used in seafood authentication, with a special focus on their characteristics, advantages, disadvantages, and how they have been employed in seafood authentication.

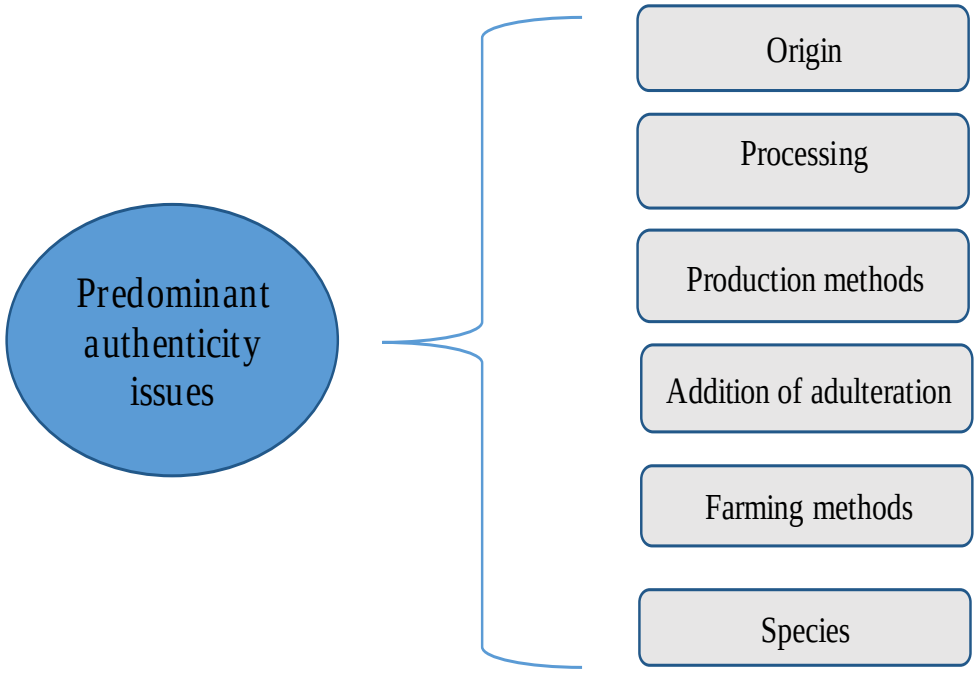

Figure 1. Predominant authenticity issues reported in food products of animal origin including fish. Adopted and modified from (Hassoun et al., 2020).

2. Methodology

2.1. Literature Search

To achieve the objective of providing an overview of the application of various spectroscopic techniques in monitoring seafood quality, studies previously published in this thematic area were searched and used. Papers published in languages other than English were excluded from this review. This prevented any kind of false information or misrepresentation because the authors were only acquainted with English. This review considered no specific duration or date of publication. Databases such as CAB abstracts, IEEE, Scopus, Web of Science, and Ajol were considered. Also, articles published in Elsevier, Taylor & Francis, and Wiley were considered. This literature review was conducted according to guidelines for systematic reviews created by (European Food Safety Authority, 2010).

2.2. Search Strings

Papers relevant to this study were identified using different words. The search strategy included keywords such as 'spectroscopy authentication,' 'seafood fraud,' 'vibrational near-infrared,' and 'nuclear magnetic resonance.

3. Spectroscopy-Based Techniques Used in Seafood Authentication

A collection of methods known as spectroscopy uses the interplay of light and matter to acquire more information about the chemical and physical makeup of materials (Vitha, 2018). Spectroscopy is a technique that measures the electromagnetic radiation that a sample emits, scatters, or absorbs in order to determine its composition, structure, and other properties (Vitha, 2018).

The analysis of seafood authenticity has been developed using spectroscopic techniques (Ghidini et al., 2019). Rephrase as "Recently, Qin et al. (2020) used multimode hyperspectral imaging techniques to detect mislabeling and fish fillet substitution. Fraud frequently occurs in seafood market and is difficult or impossible to detect through visual inspection (Silva et al., 2021). Moreover, a study was conducted to investigate the potential of two hyperspectral imaging (HSI) systems covering the visible and near infrared range (VNIR, 397–1003 nm) and the short-wave near infrared range (SWIR, 935–1720 nm), respectively, for rapidly and accurately determining adulteration in minced Atlantic salmon (Li et al., 2023). Problems with authenticity in fish and seafood products include species replacement, fabrication of geographic origin, distortion of the manufacturing process or farming system, and substitution of fresh for frozen or thawed items (Chai et al., 2021).

Spectroscopic methods can be used to examine the chemical make-up makeup of food products, including their macro-nutrients, micro-nutrients, and pollutants, in the process of food authentication (Molina et al., 2019). Spectroscopic methods have been used to assess and verify the quality of seafood, including vibrational (near-infrared (NIR), mid-infrared (MIR), and Raman), fluorescence or absorption ultraviolet-visible (UV-Vis), and nuclear magnetic resonance (NMR) (Al-Zahrani et al., 2020).

In this section, these spectroscopic-based techniques are discussed, taking into consideration their characteristics, descriptions, advantages, and limitations.

3.1. Ultraviolet and Visible (UV-Vis) Spectroscopy

The measurement of light absorption in the ultraviolet and visible portions of the electromagnetic spectrum, or UV-Vis spectroscopy, can reveal the presence or absence of particular substances, such as pigments or additives (Karoui, 2018). Vibrational and electronic excitations result in absorptions in the UV-VIS zone (Penner, 2017). Energy absorption, which can be likened to the concentration of absorbing molecules, leads to excited electrons (Van Maarschalkerweerd & Husted, 2015).

The advantages of UV-Vis spectroscopy are enormous and have been reported to include the following: the detection process can be completed quickly, the detection device can be made smaller and more portable so that it can be used in a variety of locations, and it is also difficult for the sample matrix or reagent colour to interfere because their absorption does not overlap the UV spectrum (Yuan et al., 2022) (Table 1). Also, the use of UV-VIS spectroscopy is made possible by the availability of high-quality equipment, ease of use, accuracy, precision, and speed of the technique (Snyder et al., 2014). This method can have drawbacks as Uv-vis spectroscopy can have interference from impurities or contaminants as the sample preparation can be time-consuming (Antony & Mitra, 2021). Moreover, stray light can affect the accuracy of UV-VIS spectroscopy (Picollo et al., 2019). The calibrations and maintenance is required regularly and this technique is not suitable for non-uv-absorbing molecules as they lack sensitivity to certain matrixes (Crego & Marina, 2005).

3.2. Near-Infrared Spectroscopy (NIR)

This kind of spectroscopy gauges the electromagnetic spectrum's near-infrared region's absorption of light, which can reveal details about the chemical makeup of food items such as their fat, moisture, and protein contents (Murray & Cowe, 2005). According to Nicolai et al. (2007), NIR instrumentation can be classified into the following categories based on the type of monochromator used: scanning

monochromator instruments, light filter instruments, light-emitting diode (LED) instruments, array-detecting instruments, Fourier transform (FT) NIR instruments, liquid crystal tunable filter (LCTF) instruments, and acoustic optic tunable filter (AOTF) instruments (Wang & Paliwal, 2007). The NIRS systems typically have four-chambered compartments, namely detector devices, light sources, sampling devices, and light-isolating mechanisms (Wang & Paliwal, 2007).

The basis for NIR spectroscopy is the functional groups' ability to absorb electromagnetic radiation at wavelengths between 780 nm and 2500 nm (Melado-Herreros et al., 2022). This method is advantageous as no sample preparation is necessary for NIR spectroscopy. As a result, the analysis is quick and straightforward. The NIR approach also enables the simultaneous measurement of many constituents (Pasquini, 2018). Additionally, high-moisture foods can be examined due to the relatively limited absorption caused by water (Osborne, 2010). NIR spectroscopy is an affordable and environmentally friendly monitoring technique that does not require sample pretreatment (Nordey et al., 2017) (Table 2). NIR is a screening technique that can also be utilized as an in-line tool to track any changes that can take place during food processing (At-Kaddour & Cuq, 2011).

NIR's capacity to simultaneously determine several components per measurement with a distant sampling capability and, as a result, to give real-time data from processing lines is one of its strengths. The lower frequencies of NIR can penetrate more deeply into the sample and thus are less prone to be influenced by surface effects (Karlsdottir et al., 2014).

NIR spectroscopy provides a broad picture of all the distinct compounds present, but does not provide highly detailed spectrum information, which prevents it from revealing detailed chemical information about the sample (Osborne, 2010). In addition, due to the overtones and combinations of the vibrational bonds' extremely overlapped and weak absorption bands, NIR spectra are complicated (Sandorfy et al., 2007).

3.3. Mid-Infrared Spectroscopy

Mid-infrared spectroscopy's utility stems from the mid-IR spectrum's often well-resolved absorption bands and the resulting relatively simple chemical identification and quantification (Doyle, 1994). To determine or quantify certain substances, mid-infrared spectroscopy detects the absorption of light in the mid-infrared region of the electromagnetic spectrum (Abbas et al., 2020). This method can provide details about the molecular structure of food products, such as their functional groups (Abbas et al., 2020) (Table 3). The absorption of all chemical bonds between 4000 and 700 cm^{-1} is represented by the MIR spectrum (Boughattas & Karoui, 2021). MIR spectroscopy has been widely used in industrial settings because it is easy to use and does not require huge finances and expensive equipment (Dominguez-Vidal et al., 2018). Mid-infrared spectroscopy is not applicable if the sample contains water (Reich, 2016). Additionally, mid-infrared

Table 1. Application of *UV-Vis* spectroscopic-based techniques in seafood authentication

Field of Spectroscopy	Fish and Fishery Products (Seafoods)	Findings	References
UV-Vis spectroscopy	Cuttlefish (*Sepia officinalis*)	There were not many notable variations between fresh and frozen–thawed during storage in the wet chemical and microbiological data. The quality index method and microbiological tests indicated that fresh and frozen–thawed samples behaved similarly up to about 9 days of shelf life. The main physicochemical changes of cuttlefish throughout their shelf life might be interpreted using the aquaphotomics results shown in aquagrams. A classification precision of 0.91 between fresh and frozen–thawed was attained by partial least squares discriminant analyses models with the spectral range of 900–1650 nm, while performance in predicting storage days was less successful. The water coordinates indicated that the molecular conformation of the different types of water in the frozen–thawed samples was different from that of the fresh samples, with more free water molecules and fewer bound species and water solvation shells, respectively.	(Sannia et al., 2019)
	Multi-species	By boiling fish tissue samples in trifluoroacetic acid (TFA) solution for two minutes and evaluating the resulting samples with a UV-Vis spectrometer, UV-Vis spectroscopy combined with chemometric analysis, such as principal component analysis (PCA), can precisely discriminate two fish species. The devised technique was effectively used to categorize and identify fish samples that were purchased. It is an appealing technique that can be used to classify and authenticate fish species that have similar characteristics in order to detect and recognize fish substitution.	(Chai et al., 2021)
	Fresh and frozen–thawed cod (*Gadus morhua*) fillets	Using a narrow subset of wavelengths in the visible area, frozen–thawed cod fillets and fresh fillets may be completely distinguished from one another. On individual fillets, freshness as days on ice can be estimated with a preciseness of 1.6 days. The findings suggest that the majority of the fluctuations in the visible area of the spectrum can be attributed to oxidation of hemoglobin and myoglobin during freezing–thawing and cold storage on ice.	(Sivertsen et al., 2011)
	Japanese dace fish (*Tribolodon hakonensis*)	Using multivariate analysis methods to evaluate the capacity to predict Japanese dace (Tribolodon hakonensis) freshness from ultraviolet-visible (UV-VIS) absorption spectrum characteristics of ocular fluid in the region of 250–600 nm proved an accurate tool.	(Anisur, 2015)
	Japanese dace fish (*Tribolodon hakonensis*)	With a determination coefficient of prediction (R^2_{pred}) of 0.87 and a root mean square error of prediction of 7.87%, the regression model created by PLS based on multiplicative scatter correction preprocessed spectra performed better than models created by other preprocessing approaches. With the right multivariate analysis and UV-VIS spectroscopy, it may be possible to predict the K value of fish flesh with accuracy.	(Rahman et al., 2016)

spectroscopy is limited to certain conditions for quantitative analysis (Mendes & Duarte, 2021). Mid-infrared spectroscopy has complications in fully clarifying the compound structure based on a single infrared radiation spectrum (Rodriguez-Saona et al., 2016).

3.4. Raman Spectroscopy

Raman spectroscopy is a harmless spectroscopic method that employs light dispersion to generate altered energy frequencies (Ojha et al., 2022). Raman signals are formed by the inelastic scattering of light from the samples to be studied, and the consequent frequency shift reveals the stretching vibrations involved (Boyaci et al., 2015) (Figure 2).

The molecular vibration technique known as Raman spectroscopy is based on inelastic Raman scattering, a physical phenomenon that results from molecular vibrations and changes the polarizability of the molecule (Boyaci et al., 2015). Raman spectroscopy examines how light is scattered by molecules in a sample, which can reveal information about the sample's molecular structure and chemical composition

Table 2. Application of NIR spectroscopic-based techniques in seafood authentication

Field of Spectroscopy	Fish and Fishery Products (Seafood)	Findings	References
NIR Spectroscopy	Grass carp fillets	NIR system in the spectral range of 400–1100 nm was demonstrated to be potential and feasible for rapid and non-invasive detection of TVC values of grass carp fillets. Both of the quantitative PLSR and LS-SVM models established using full wavelengths presented excellent performance with RPD of 3.80, 3.89, 0.93, and 0.93 and RMSEP of 0.50 and 0.49 $\log_{10}$ CFU/g.	(Cheng & Sun, 2015)
	Horse mackerel	The total absorbance level was found to decrease in dry extract spectroscopy by infrared reflection spectra for frozen–thawed samples, showing that the chemical composition of juice, the amount of dry matter, the size of the particles, and their scattering characteristics differ. The 1920–2350 nm range is where the spectrum differences between fresh and frozen–thawed materials may be readily noticed. Peaks in the spectra that have been linked to proteins predominate, particularly those at 1510, 1700, 1738, 2056, 2176, 2298, and 2346 nm. It was discovered that the dry extract spectroscopy by infrared reflection approach could completely distinguish between fresh and frozen–thawed fish.	(Uddin & Okazaki, 2004)
	Red sea bream (*Pagrus major)*	Nondestructive visible/near-infrared (NIR) spectroscopy was evaluated to investigate whether fish had been frozen–thawed. Fresh or frozen–thawed red sea bream *Pagrus major* (*n* = 108) were scanned using a NIR Systems 6500 spectrophotometer equipped with a surface interactance fiber-optic accessory, then discriminated by soft independent modeling of class analogy (SIMCA) and linear discriminant analysis (LDA) based on principal component analysis (PCA) scores.	(Uddin et al., 2005)
	Walleye pollack and horse mackerel surimi	The study demonstrates the potential of visible–NIR reflectance spectroscopy for determining heating adequacy of fish-meat gels in a rapid, reliable, and non-destructive manner. Once perfected, this technique will have several advantages over other techniques, in that it will take the least time for analysis and will not require any consumables or supporting equipment.	(Uddin et al., 2005)
	Bigeye tuna (*Thunnus obesus*)	The outcomes of this study emphasized the ability of three non-destructive sensors (BIA, NIR, and TDR) to distinguish between fresh and frozen–thawed tuna samples that may or may not have added water, a circumstance that could occur in the fish business and market. NIR performed the best classification, with an accuracy in the model of 0.91 and an error rate of 0.10 through the verification period.	(Nieto-Ortega et al., 2021)
	Chill-stored thawed cod fillets	NIR measurements offered encouraging outcomes for modified atmosphere packaging of fish fillets that had been thawed and refrigerated, rounding out the usually high-quality techniques. The correlation coefficient between the actual and anticipated length of the chill storage time (days at 2 °C), as predicted by partial least-squares regression models based on wavelengths chosen by a new Jack-knife approach, was 0.90.	(Bøknæs et al., 2002)
	Atlantic salmon	The NIR spectra clearly distinguished between the fresh salmon fillets and those kept for nine days at 4 °C, proving that the technology could identify spoilage. The NIR spectra acquired when the fish was fresh were used to forecast the amount of bacteria that would be present nine days later using a partial least squares regression prediction model for total aerobic plate counts. Although the inaccuracy of the validation curve was greater (R^2 = 0.64 and RMSE = 0.32 log cfu/g), the calibration equation was sound (R^2 = 0.95 and RMSE = 0.12 log cfu/g). These findings suggest that, with additional model development, NIR might be used to forecast bacterial populations and, consequently, shelf-life in Atlantic salmon and other seafood.	(Tito et al., 2012)
	Swordfish cutlets (*Xiphias gladius*)	The percentage of samples that were successfully classified using NIR was 90.0%. A multivariate binary logistic regression was employed in conjunction with the more descriptive principal component scores of NIR. Using NIR to compare fresh and frozen–thawed samples, the classification rate was 96.7%.	(Fasolato et al., 2012)
	Atlantic salmon (*Salmo salar L.*) fillets	The main factor responsible for spectral alterations is the oxidation of heme proteins during the freeze–thaw cycle and cold storage in ice.	(Kimiya et al., 2013)
	Wild European Sea Bass (*Dicentrarchus labrax*)	NIRS may be used to distinguish between wild and farmed sea bass with high accuracy, outperforming approaches that classify objects based on chemical characteristics and morphometric attributes. NIRS-based categorization techniques are easier, quicker, more cost-effective, and safer for the environment because they do not need reagents. All methodologies suggested that the spectrum regions associated to the absorbance of groups CH, CH2, CH3, and H2O, which are connected to fat, fatty acids, and water content, were the most foretelling.	(Ottavian et al., 2012)

Table 3. Application of MIR spectroscopic-based techniques in seafood authentication

Field of Spectroscopy	Fish and Fishery Products (Seafood)	Findings	References
	Sea bream (*Sparus auratus*) and salmon (*Salmo salar*)	The NIR and MIR spectra discriminated between the samples mainly on the basis of lipid oxidation and protein degradation. Results suggested that spectroscopic techniques could be useful tools for a rapid and easy evaluation of fish freshness during storage in ice. This approach proved viable in particular for sea bream and for fish fillets.	(Alamprese et al., 2011)
	Sevruga (*Acipenser stellatus*)	Mid-infrared spectroscopy could be employed as a rapid screening tool to discriminate rapidly between fresh and frozen–thawed *Sevruga* fish, since 92.16% of correct classification was obtained.	(Vilkova et al., 2023)
MIR spectroscopy	Twenty-four whiting fillets (*Merlangius merlangus*) were analyzed	From the study, 3000–2800 cm^{-1} and 1500–900 cm^{-1} spectral regions may provide useful fingerprints allowing the differentiation between fresh and frozen–thawed fish. These regions can be considered as a reliable indicator of fish freshness.	(Karoui et al., 2007)
	Atlantic bluefin tuna (*Thunnus thynnus*), crevalle jack (*Caranx hippos*), and Atlantic Spanish mackerel (*Scomberomorus maculatus*) fillets	Mid-infrared spectroscopy (MIR) and a partial least square algorithm (PLS-1) were used to predict the deterioration indices, pH, and chemical composition of Atlantic bluefin tuna, crevalle jack, and Atlantic Spanish mackerel chilled fillets.	(Hernández-Martínez et al., 2014)

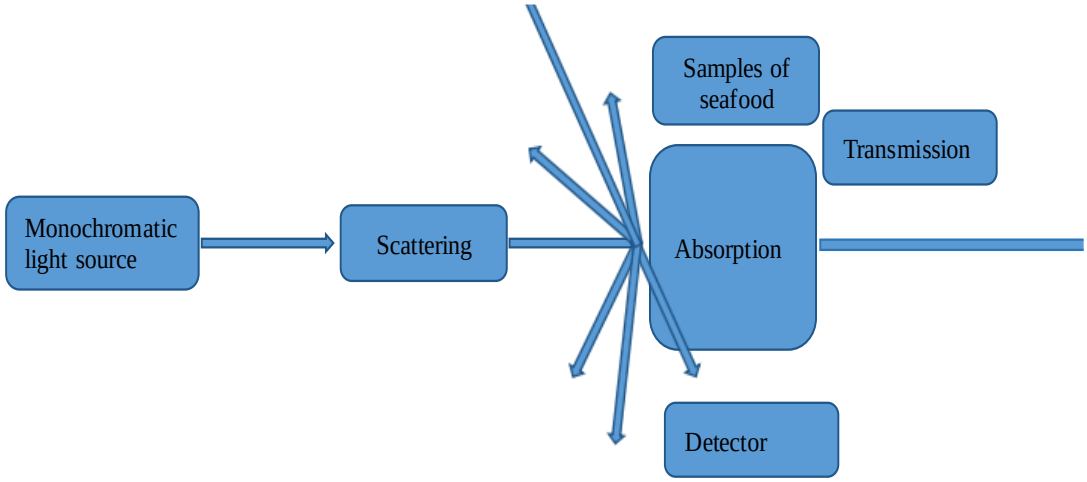

Figure 2. Schematic representation of Raman spectroscopy. Adopted and modified from (Chaudhary et al., 2022).

(Eberhardt et al., 2015). Additionally, it can be used to quantify or identify specific compounds (Rostron et al., 2016).

Raman spectroscopy has many benefits, including being non-destructive, rapid, practical, and providing accurate detection in addition to thorough fingerprinting (Shah et al., 2023). Also, it is an effective analytical method for quickly and non-destructively measuring vibrational energy levels (Su et al., 2017). Although Raman spectroscopy is practically more difficult to use in the industry, the technique may have significant benefits in terms of resilience (Lintvedt et al., 2022). Raman spectroscopy is an important form of spectral analysis that is pollution-free, non-destructive, and highly sensitive (Xu et al., 2020). Raman spectroscopy can be used to distinguish between production methods, ingredient ratios, different breeds and regions (wild or farmed), and the presence of illicit additions (Ortea et al., 2016; Esteki et al., 2019; Bohme et al., 2019).

Raman spectroscopy has its own disadvantages, which include its high sensitivity and the requirements of high-level optimization, which is essential for detection (Zhang et al., 2017). In addition, Raman spectroscopy shows high fluorescence in samples or impurities, which can affect the Raman spectrum (Wei et al., 2015). Similarly, it requires technicians who are skilled because of the complex nature of its data analysis (Chaudhary et al., 2018; Xu et al., 2020).

3.5. Fluorescence Spectroscopy

A non-invasive method for finding fluorophores, such as amino acids, vitamins, and aromatic organic materials, is fluorescence spectroscopy (Nielsen et al., 2023). Fluorescence spectroscopy is a sensitive and focused spectroscopic method that has lately been widely used to address a variety of concerns related to the quality and authenticity of food (Hassoun, 2021). Fluorescence spectroscopy can detect the light that is released when fluorophores are stimulated (Nielsen et al., 2023). It measures the amount of light that molecules in a sample emit when activated by a light source, which can reveal the presence or absence of

certain substances like pollutants or vitamins (Bose et al., 2018).

More intriguingly, fluorescence spectroscopy has been described as an effective and promising technology to control food quality and authenticity due to its great sensitivity and selectivity (Kumar et al., 2017; Hassoun et al., 2019). This technique relies on detecting the presence of naturally occurring fluorescent molecules (fluorophores) without doing substantial sample processing or handling potentially harmful chemicals (ElMasry et al., 2015).

3.6. Nuclear Magnetic Resonance (NMR) Spectroscopy

A physicochemical method called nuclear magnetic resonance (NMR) spectroscopy is used to identify the structural characteristics of molecules (Hatzakis, 2019). Nuclear magnetic resonance (NMR) spectroscopy is an extremely flexible method for analyzing food (Lesot et al., 2023). NMR spectroscopy is very popular due to its untargeted applications (Sacchi & Paolillo, 2007). The four main sections of NMR spectroscopy, as shown in Figure 3, include a radio frequency receiver, a very stable radio frequency transmitter, a recorder or monitor, and a magnet with pole ends that have a very uniform magnetic field (Parlak & Guzeler, 2016).

Phase shifts, conformational and configurational modifications, solubility, and diffusion potential can all be identified using nuclear magnetic resonance spectroscopy (Krishnan, 2019). NMR spectroscopy provides rapid data acquisition, has a high resolution, and is non-destructive (Mor et al., 2020). A typical drawback is NMR devices' inadequate sensitivity to insufficient sample concentrations, resulting in unsatisfactory spectra (Emwas et al., 2019). The instrument's limited sensitivity is related to the weak interaction energies of NMR magnetic resonance with the sample molecules (Günther, 2013). NMR devices as well as upkeep are costly since they demand big and potent magnets for energy and cryogenic fluids for conditioning (Wikus et al., 2022). Due to the intricacy and complexity in deciphering the spectra, NMR spectroscopy is ineffective for analyzing greater molecular weight compounds (Matthews, 2022).

3.7. Fourier Transform Infrared (FTIR) Spectroscopy

The Fourier transform spectroscopic technique is categorized under vibrational spectroscopy which employs interferometers to modulate the Fourier transform algorithm in the form of an electromagnetic signal to transform sample data into an optical spectrum obtained on a computer system (Jaggi & Vij, 2006). In the interferometer, light beams are scattered and then reassembled (Yang et al., 2015). Due to the simultaneous measuring of wavelengths, this approach is quick and has a better signal-to-noise ratio (Wahab et al., 2021). The Fourier transform can be also used in optical, infrared, nuclear magnetic resonance, Raman, electron spin resonance spectroscopies as well as mass spectrometry. However, this method is generally applied to infrared spectroscopy (Dutta, 2017). This method has been employed in the seafood authentication of fish and fishery products (Fengou et

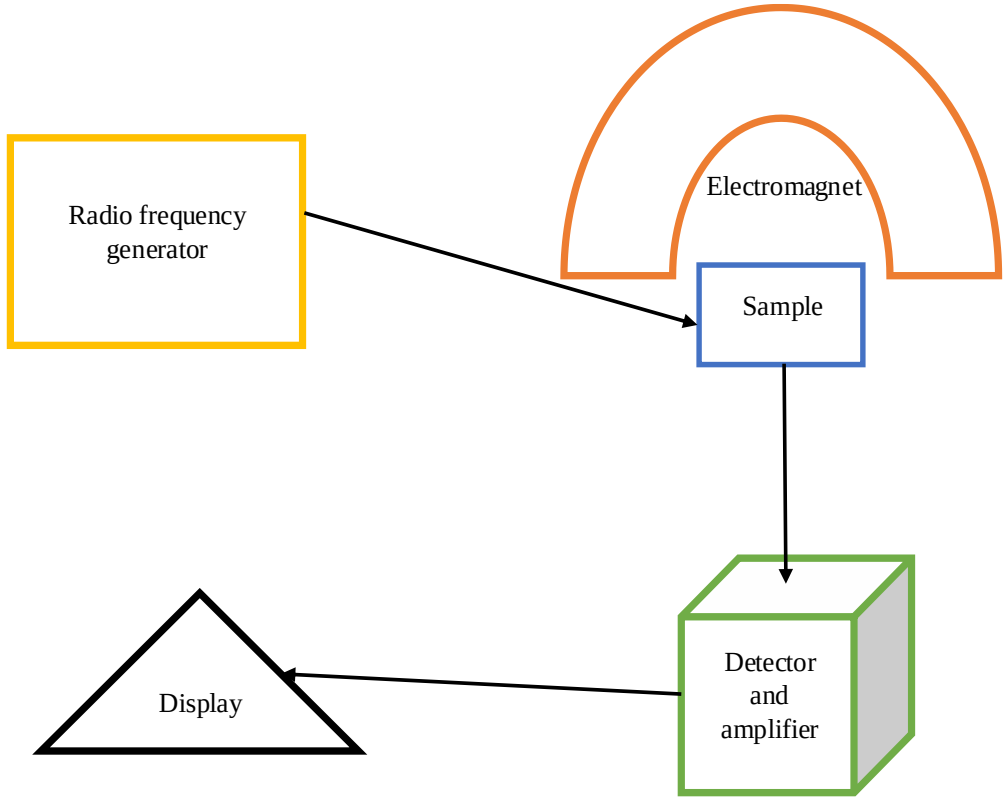

Figure 3. Schematic representation of NMR spectroscopy. Adopted and modified from (Chaudhary et al., 2018).

al., 2019) (Table 4). Additionally, this spectroscopic technique is successfully utilized for the detection and characterization of different types of adulterants in meat and processed meat products (Moreira et al., 2017).

4. Applications of Spectroscopic-Based Techniques in Fish and Fishery Products' (Seafood) Authentication

The application of techniques based on spectroscopy in seafood authentication has been studied by several researchers (Alamprese & Casiraghi, 2015; Rašković et al., 2016). For instance, Gayo & Hale. (2007) studied the application of Vis-NIR spectroscopy as a technique to detect the counterfeiting of blue swimmer crab meat (*Portunus pelagicus*) with blue crab meat (*Callinectes sapidus*).

The principal features of the crab meat spectra were found to be dominated by bands of water absorption, and the scientists found that as the proportion of adulteration increased, the sample absorbance decreased (Gayo, 2006; Gayo et al., 2006; Gayo & Hale, 2007). Gayo et al. (2006) employed the use of prediction and quantitative analysis using raw data, a 15-point smoothing average, a first derivative, a second derivative, and 150 wavelength spectral data gathered from a correlogram.

Prior to creating PLS regression models, these authors also reported using a number of data pre-treatments on the NIR spectra, such as a moving average, a mix of first and second derivatives, as well as the use of multiplicative scatter corrections in addition to the raw data (Gayo, 2006; Gayo et al., 2006; Gayo & Hale, 2007). It has been discovered that chemometric techniques and VIS and NIR spectroscopy were effective for identifying and measuring species authenticity and adulteration in crabmeat (Gayo, 2006; Gayo et al., 2006; Gayo & Hale, 2007). Also, Raman spectroscopy was used to establish a classification model of fish species and spectra obtained were in the range of 200–2000 cm^{-1} with a resolution of 2 cm^{-1}. Measurements were conducted in duplicate for each sample (Velioglu et al., 2015). Not long ago, the spectral properties of ultraviolet-visible (UV-VIS) were employed to predict the K value of fish flesh for the assessment of its freshness and for each sample, the spectrum was recorded from 250 to 600 nm at a bandwidth of 0.5 nm and a scan speed of 400 nm per minute (Rahman et al., 2015).

PCA and NIR spectroscopy were employed to distinguish between shrimp (*Pandalus borealis*) and a commercial freezer trawler by (Brodersen & Bremner, 2001). The authors showed that the ability to distinguish between frozen and thawed material, between the salt content, pH in the flesh, cooking period (temperature), as well as the whole or minced shrimp, was achieved by combining chemometrics with NIR spectra obtained from samples of whole shrimp and of minced fresh shrimp from the various treatments (Brodersen & Bremner, 2001).

The ability of VIS-NIR spectroscopy and a hyperspectral imaging system to distinguish between fresh, cold-stored, and frozen–thawed shelled shrimp

Table 4. Application of FTIR spectroscopic-based techniques in seafood authentication

Field of Spectroscopy	Fish and Fishery Products (Seafood)	Findings	References
FTIR spectroscopy	Atlantic salmon (*Salmo salar*) and Salmon trout (*Onconrhynchus* mykiss)	The proposed methods have the advantage of allowing quick measurements, despite the storage time of the adulterated fish. FTIR combined with chemometrics showed that a methodology to identify the adulteration of *Salmo salar* with *Onconrhynchus mykiss* can be established, even when stored for different periods of time.	(Sousa et al., 2018)
	Alaska pollock and two species (Sablefish and Antarctic toothfish)	Based on the developed detection model, adulterants in Alaska pollock could be rapidly detected and accurately quantified. In addition, it provides a reliable basis for rapid and non-destructive detection of and has great potential for determining other seafood species.	(Feng et al., 2024)
	Marine oil	These simple, rapid, and nondestructive spectroscopic procedures have the potential for differentiating between natural and concentrated forms of omega-3 PUFA and verifying the accuracy of label declarations.	(Karunathilaka et al., 2019)
	Gilthead seabream (*Sparus aurata*) adults	FTIR can be applied to disclose the metabolic alterations in the fish liver as a result of exposure to standard stressful practices in aquaculture.	(de Magalhães et al., 2020)
	Adult male Crayfish (*Astacus leptodactylus*)	The suitability of FTIR spectral data to analyze the metabolic-induced effects of polyphenolic-enriched diets in crayfish hepatopancreas.	(Volpe et al., 2018)
	Atlantic fresh and thawed mullets	FT-IR spectroscopy showed a better classification ability both for species and fresh–thawed fillet identification, but it needs a sample preparation, although this is simple.	(Alamprese & Casiraghi, 2015)
	Menhaden fish oil	FTIR was used for evaluating oxidative quality and application of artificial neural network analysis (ANN), a mathematical model, and to predict the oxidative values of Menhaden fish oil.	(Klaypradit et al., 2011)
	Different brands of canned tuna and other tuna-like species in a variety of olive (48) and seed (42) oils	The authentication of packing oil from commercial canned tuna and other tuna-like fish species was examined by means of attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR) and chemometrics. Using partial least squares discriminant analysis (PLS-DA), it was possible to differentiate olive oil from seed oils.	(Dominguez-Vidal et al., 2018)

(*Metapenaeus ensis*) was established by (Qu et al., 2015). The study's findings showed that chemometrics and spectroscopy combined were effective for finding items that had been replaced and mislabeled unlawfully (Qu et al., 2015). With classification rates greater than 91% and 88%, respectively, their study revealed the value of using VIS-NIR (400–1000 nm) spectroscopy to distinguish between fresh shrimps and those from either cold storage or freezing (Qu et al., 2015). Chemometric approaches were used alongside hyperspectral imaging to evaluate the precision and dependability of the method for spotting gelatin adulteration in prawns (Wu et al., 2013).

In another study, NIR spectroscopy was used to verify the authenticity of wild European sea bass (*Dicentrarchus labrax*) (Ottavian et al., 2012). The ability of the three chemometric processing methods the authors investigated to distinguish between samples of wild and farmed sea bass was assessed (Ottavian et al., 2012). The three chemometric techniques showed that NIR spectroscopy may be used to consistently distinguish between wild and farmed sea bass, providing classification results on par with those of methods that rely on chemical characteristics and morphometric attributes (Ottavian et al., 2012). In addition, compared to conventional approaches based on chemical analyses, NIR-based categorization methods are less complicated, quicker, more affordable, and ecologically safe. They also do not require reagents (Ottavian et al., 2012).

A study by Lv et al. (2017) utilized NIR spectroscopy to discriminate between different species of freshwater fish, including black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idellus*), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Aristichthys nobilis*), common carp (*Cyprinus carpio*), crucian (*Carassius auratus*), and bream (*Parabramis pekinensis*), which were scanned by near-infrared reflectance spectroscopy from 1000 nm to 1799 nm. The model that was based on PCA-LDA and FFT-LDA showed 100% prediction accuracy. The use of the model on spectra effectively simplified the discrimination model. The model was used to select the effective wavelengths by analyzing the loadings of variables for the principal components. The authors came to the conclusion that the methods devised were successful at differentiating various freshwater fish species (Lv et al., 2017).

A quick method to recognize important species was also tested using IR spectroscopy (e.g., red mullet (*Mullus surmuletus*) and plaice (*Pleuronectes platessa*) substitution with cheaper varieties (e.g., Atlantic mullet (*Mugil cephalus*) and flounder (*Paralichthys dentatus*) in combination with LDA and SIMCA. The near-infrared (NIR) spectra were recorded (12 cm^{-1} resolution; 64 scans both for background and samples) on the flesh side of the whole fillet previously conditioned at room temperature, by using a Fourier transform (FT)-NIR spectrometer (MPA, Bruker Optics, Ettlingen, Germany) fitted both with an integrating sphere (spectral range: 12,500–3750 cm^{-1}) and an optical fiber (spectral range: 11,000–4400 cm^{-1}) **(**Alamprese & Casiraghi, 2015). The ability of Fourier transform MIR (FT-MIR) was also evaluated by Wu et al. to study the adulteration of Norwegian salmon with Heilongjiang salmon at local fish markets (Wu et al., 2017). The authors reported that the Norwegian and Heilongjiang salmon samples could be identified using PLS-DA. However, the method was unable to classify the extent of adulteration between levels of 20–80% (Wu et al., 2017).

The use of NIR and hyperspectral imaging (900–1700 nm) was evaluated as a tool to automatically check fish quotas (Ramirez & Pezoa, 2018). The authors assumed that different small pelagic fish species have different spectral signatures (Ramirez & Pezoa, 2018). In this study, samples of Chilean silverside (*Odontesthes regia*), southern rays bream (*Brama australis*), and silver hake (*Merlucciidae*) were scanned and their spectral signatures were analyzed using the k-nearest neighbor (k-NN) and SVM (Ramirez & Pezoa, 2018). The authors reported classification rates between 80% and 90%, depending on the NIR region used during the development of the application (Ramirez & Pezoa, 2018).

Raman spectroscopy (wavelength of 532 nm) was evaluated to classify deep frozen fish fillets (Rašković et al., 2016). The spectra of the fillet samples sourced from twelve types of fish were scanned using Raman spectroscopy and analyzed using hierarchical clustering. The authors identified three groups, namely fish from the salmonid family; the second group comprised of fish reared in fresh or brackish water; and the third group comprised of saltwater-reared fish. The authors demonstrated the potential of Raman spectroscopy as a screening tool prior to the routine, with standard industry methods for the identification of fish fillets (Rašković et al., 2016).

The potential of VIS and NIR hyperspectral (400–1000 nm) imaging as a rapid and non-invasive method to assess the freshness of prawns was investigated by (Dai et al., 2015). The authors evaluated both unfrozen and frozen samples (280 prawns total) and reported the rapid non-invasive classification of unfrozen and frozen prawn samples with an average correct prediction rate of 98.33% and 95%, respectively (Dai et al., 2015). The authors noted that their study should encourage greater research efforts with regard to the online application of hyperspectral imaging for the classification and prediction of seafood products. However, they also acknowledged that as the number of samples analyzed in the study was low and only a limited number of storage periods were investigated, additional samples possessing a more varied range of freshness levels should be considered to improve the accuracy and reliability of the models in future studies. The authors also recommended that more advanced algorithms should be developed to determine the relationship between freshness and hyperspectral datasets (Dai et al., 2015).

The rapid and non-destructive assessment of silver chub (*Macrhybopsis storeriana*) freshness using FT-NIR spectroscopy was reported by (Ding et al., 2014). The authors reported that the eyeball of the fish was in the best position to locate the NIR fiber optic in order to collect the spectra (Ding et al., 2014). The main explanation of this by the authors was related to the structure of the fish eyes and the direct relationship that exists between eye characteristics and the overall freshness of the fish during cold storage (Ding et al., 2014). The authors reported that the combination of spectral analysis combined with chemometrics successfully identified the freshness of samples with a correlation coefficient of 95.59% (Ding et al., 2014). Similarly, Zhou et al. (2019) determined the freshness of the big head carp (*Hypophthalmichthys nobilis*) with NIR spectroscopy combined with different regression methods. Samples were scanned in a reflectance mode covering the spectral range of 1000–1799 nm. The authors reported the prediction of chemical parameters directly associated with freshness using NIR spectroscopy, such as the pH, total volatile basic nitrogen (TVN), and thiobarbituric acid (TBARS) (Zhou et al., 2019). The prediction models reported a yield with a coefficient prediction of 0.945, 0.932, and 0.954 and a root mean square error of prediction of 0.081, 2.099, and 0.107 for pH, TVN, and TBARS, respectively (Zhou et al., 2019).

In another study, Saraiva et al. (2017) reported the use of FT-MIR to identify and monitor the spoilage of salmon samples stored in three different environments in real time. The homogenized salmon samples were analyzed using an attenuated total reflectance (ATR) cell, where PCA was used to identify the regions in the MIR region associated with the spoilage process (Saraiva et al., 2017). The researchers also used LDA to analyze the MIR spectral data in combination with sensory data to better quantify sample freshness. All infrared spectra were recorded from 900 to 2000 cm^{-1}, co-adding 128 interferograms at a resolution of 2 cm^{-1} (Saraiva et al., 2017). The use of hyperspectral imaging to monitor freshness in cod fillets (freeze storage, thawing, vacuum packed) was reported (Washburn et al., 2017). The authors concluded that the freezing history could be predicted for frozen and thawed samples (Washburn et al., 2017).

The combination of VIS and NIR hyperspectral imaging was evaluated to differentiate between frozen and frozen samples of halibut (*Psetta maxima*). The hyperspectral images of fillets were captured using a pushbroom hyperspectral imaging system in the spectral region of 380 to 1030 nm (Zhu et al., 2013). For the prediction samples, the authors' stated categorization rates were greater than 97% (Zhu et al., 2013). However, when the various freezing rates were taken into account, the categorization rates were lower. The authors came to the conclusion that fresh and frozen–thawed samples could be distinguished using VIS and NIR hyperspectral imaging (Zhang et al., 2018). More information on the cutting-edge use of hyperspectral imaging to monitor fish's freshness, safety, and storage conditions was found in a recent article (He et al., 2015).

In order to identify and categorize the species of fish and assess their freshness, Raman spectroscopy was examined (e.g., freezing vs. thawing) with spectra that were obtained in the range of 200–2000 cm^{-1} with a resolution of 2 cm^{-1}. Measurements were conducted in duplicate for each sample (Velioglu et al., 2015). The fish species analyzed in this study included horse mackerel (*Trachurus trachurus*), European anchovy (*Engraulis encrasicolus*), red mullet (*Mullus surmuletus*), bluefish (*Pomatamus saltatrix*), Atlantic salmon (*Salmo salar*), and flying gurnard (*Trigla lucerna*) (Velioglu et al., 2015). Three batches of samples were defined as fresh, once frozen–thawed, and twice frozen–thawed in this study by the authors, who divided the samples into distinct freezing and thawing cycles. PCA models were used to analyze the Raman data. The Raman approach, according to the authors, could distinguish and categorize fresh and frozen samples with up to 99.29% confidence (Velioglu et al., 2015).

5. Challenges of the Application of Spectroscopy in Seafood Authentication

5.1. Complexity of Sample Matrices

The complexity of food matrices, which frequently comprise a variety of chemical compounds and structural elements, can impair the accuracy and precision of spectroscopic approaches (Baeten et al., 2015). Seafood samples can contain various components like proteins, fats, moisture, and contaminants, making it difficult to identify specific spectral signatures (Gopi et al., 2019). One of the main drawbacks of some techniques of spectroscopy is that not all materials can be excited to fluorescence due to the lack of intrinsic fluorophores (Panigrahi & Mishra, 2018). On the other hand, the presence of several fluorophores in the examined samples may lead to overlapping peaks, which makes the identification of specific fluorophores more complicated (Bose et al., 2018). Spectroscopic techniques such as infrared (IR), Raman, and nuclear magnetic resonance (NMR) spectroscopy generate complex datasets with numerous peaks, and interpreting these spectra in the presence of a complex matrix can be challenging (Ghidini et al., 2019). For example, in an NMR spectrum, overlapping signals from different compounds (proteins, lipids, and water) in the seafood matrix can make it difficult to isolate the signals that are characteristic of a specific species or adulterant (Ghidini et al., 2019).

5.2. Variations in Sample Properties

Differences in sample properties, such as the moisture content, particle size, and temperature, can

affect the spectral signals obtained, leading to variability in the results (Nawrocka & Lamorska, 2013). Additionally, in some spectroscopic techniques, factors including color, absorbance, scattering, turbidity, and particle size may have an impact on how accurately solid samples are measured (Marquardt & Wold, 2004). Variations in sample properties can reduce the robustness of calibration models, making them prone to errors and bias (Saeys et al., 2019). Additionally, variations of sample properties can make it harder to identify outliers or anomalous samples which is critical in authentication (Li et al., 2024).

5.3. Spectral Interferences

Spectral interference is a significant challenge in the application of spectroscopy to seafood authentication because it can lead to difficulties in accurately distinguishing between different compounds, species, or detecting adulteration in seafood products (Ghidini et al., 2019: Hassoun et al., 2020). Spectral interferences occur when the analyte of interest is affected by other constituents in the sample, leading to inaccurate or misleading results (Ghidini et al., 2019). Seafood often undergoes various processing treatments (e.g., freezing, cooking, smoking, drying, or canning), which can alter its chemical composition and introduce new compounds or modify existing ones (Ghidini et al., 2019). Overlapping spectral bands from different components in seafood samples could cause spectral interferences (Ghidini et al., 2019). Fluorescence from the sample matrix component could cause spectral interferences (Hassoun et al., 2019). Interactions between sample components and the spectroscopic instrument could lead to spectral interference which could lead to inaccurate results (Ghidini et al., 2019). Noise resulting could cause spectral interferences affecting the quality of the data (Ghidini et al., 2019).

5.4. Need for Calibration Models

Spectroscopic methods require robust calibration models to be developed, which can be time-consuming and require substantial amounts of data (Chaudhary et al., 2018). The calibration model must be trained on a wide and diverse range of samples to ensure it can handle the variability inherent in seafood products (Goyal et al., 2024). Additionally, quantifying multiple analytes or contaminants requires multiple calibration models (Gopi et al., 2019). Models for calibrations can be sensitive to instrumental variations, requiring careful instrument standardization (Nelson, 2017). Models require regular updates to adapt to the changing seafood production and processing practices (Cheng et al., 2013). Calibration models must account for various factors like the species, origin, processing, and storage conditions, making them complex (Ghidini et al., 2019).

5.5. Requirements for Specialized Equipment

Spectroscopic methods often require specialized and expensive equipment, making it challenging for some laboratories to adopt the techniques (Chaudhary et al., 2018). Additionally, some approaches can be difficult to employ effectively and comfortably due to their complicated equipment (Gopi et al., 2019). When making the measurement, expensive lasers, detectors, and filters are needed, as well as a high level of optical sampling variance (Hassoun & Karoui, 2017).

5.6. Limited Spectral Range

Certain spectroscopic techniques have limited spectral ranges, which can make it difficult to analyze a range of food constituents (Ghidini et al., 2019). Some measurement methods cannot detect molecules at very low concentrations, which places a restriction on higher ranges (Hassoun et al., 2020). A limited spectral range may not capture crucial information for authentication such as subtle changes in the molecular structure (Ghidini et al., 2019). Additional sampling may be required for instruments with limited spectral ranges (Hassoun & Karoui, 2017). Moreover, instruments with a limited spectral range may not be able to detect multiple contaminants or adulterants simultaneously (Munjanja & Sanganyado, 2015).

5.7. Expertise in Data Analysis

Spectral data analysis requires expertise in chemometrics and statistics, which may not be available in all laboratories (Kharbach et al., 2023). Additionally, specialists would be needed due to the intricacy of particular spectroscopic spectra and the requirement to create calibration models based on the application of chemometrics to forecast unknown materials (Xu et al., 2020). Developing and validating calibration models demands advanced data analysis skills as poor data analysis can lead to inaccurate or misleading results, compromising seafood authentication (Valand et al., 2020).

5.8. Limited Sensitivity

Some spectroscopic techniques have limited sensitivity, making it difficult to detect low levels of analytes in complex food matrices (Ghidini et al., 2019). Spectroscopic-based techniques can be sensitive to environmental factors such as temperature, humidity, and instrumental variability, which can affect the accuracy and reliability of results (Chaudhary et al., 2018). The main drawback of some techniques is that it is so strongly dependent on environmental variables such as temperature, pH, viscosity, and sample color (Chaudhary et al., 2018). In Florescence Spectroscopy, a fluorophore's interaction with other chemicals in the system may cause quenching processes, which reduce

the fluorescence intensity and alter the form of the spectra (Deshpande, 2001).

5.9. Failure to Predict Some Sensory Attributes

Due to the highly varied nature of fish samples and the low precision and subjectivity of the reference method, certain techniques have limits in their capacity to predict the sensory characteristics of fish (Hassoun & Karoui, 2017). Spectroscopy may not capture complex interactions between components affecting sensory attributes (Su et al., 2017). Prediction models may not generalize new, unseen samples or different instruments well (Kashani et al., 2023). Additionally, sensory attributes may be influenced by factors not measurable by spectroscopy (e.g., handling, storage) (Nenadis et al., 2017).

6. Possible Solutions to Improve Spectroscopic-Based Techniques for Food Authentication

Enhancing spectroscopic methods for food verification can be accomplished by employing multiple crucial strategies (Zong et al., 2018). First, advancing the sensitivity and specificity of these techniques by integrating machine learning algorithms and artificial intelligence can enhance the accuracy of the detection and differentiation of food products (Wang et al., 2022). Second, developing portable and cost-effective spectroscopic devices would enable a broader application in various settings, including field testing and routine quality control in the food industry (Mirkouei, 2020). Additionally, standardizing protocols and creating comprehensive spectral databases for different food types can improve the consistency and reliability of the results (Medina et al., 2019). Collaborative efforts between researchers, industry stakeholders, and regulatory bodies are essential to address these challenges and implement robust spectroscopic solutions, ultimately ensuring the authenticity and safety of food products for consumers (Aleixandre-Tudó et al., 2020). In this section, we briefly describe these possible solutions to improve spectroscopic-based techniques for food authentication.

6.1. Integration of Multiple Spectroscopic Techniques

The limits of individual spectroscopic techniques may be addressed and the accuracy and dependability of food authentication increased by combining their strengths (Medina et al., 2019). Fluorescence analysis may vary depending on where the measurements are taken because fish and meat products are heterogeneous matrices (Hassoun et al., 2019). Multispectral and hyperspectral imaging techniques have been developed to get both spectral and spatial information on a substantial portion of the analysed samples, which are more typical of the original fish or meat product, in order to get over this constraint (Fan & Su, 2022). This method provides both spectral and spatial information, which implies that a full spectrum is collected at various points of the fish sample (Fan & Su, 2022). Some spectroscopic methods have a number of inherent benefits, such as the NMR instrument's ability to interact with the item under study using electromagnetic waves in the radiofrequency region (Pérez-Jiménez et al., 2020). Due to this, the majority of NMR procedures are quick, non-destructive, non-environmentally harmful, and non-invasive. Since the factors have distinct relaxation durations, this method can be used for the quick analysis of fat, water, and/or protein (Emwas et al., 2020). NMR might also be a superior option for studying diverse materials like fish and other seafood (Ghidini et al., 2019).

6.2. Development of Robust Calibration Models

Strong calibration models that account for changes in sample characteristics and spectrum interferences must be created in order to increase the precision and accuracy of spectroscopic techniques (Workman, 2018). The fundamental idea behind developing calibration models is that an element's intensity can provide information about its concentration (Workman, 2018). The application of robust calibration models leads to the determination of content uniformity as robust models can be applied to various food types, processing conditions, and geographical origins, making the techniques more versatile (Workman, 2018).

6.3. Standardization of Sample Preparation and Methods

There is a need for the standardization of spectroscopic-based techniques to ensure that results are reproducible and comparable across studies (Workman, 2018). The standardization of sample preparation protocols can reduce variations in sample properties and improve the reproducibility of spectroscopic results (Morais et al., 2019), increasing the amount of information that can be gleaned from the sample and comprehending the influence and changes in the relationship between the texture that is obtained at the macroscopic level and the structure that is determined at the molecular level (Ge et al., 2022).

6.4. Adoption of New Technologies

Emerging technologies, such as hyperspectral imaging and terahertz spectroscopy, may offer new opportunities for food authentication and overcome some of the limitations of existing techniques (Khushbu et al., 2022). Additionally, compared to conventional IR transmission spectroscopy, several of these new spectroscopy technologies offer a quick analytical tool that requires less sample preparation, improves sample-to-sample consistency, and reduces user-to-user spectrum variance (Pasquini, 2018). Additionally, the

use of DNA methods has been accompanied with other techniques in seafood authentication (Filonzi et al., 2023). Artificial intelligence methods have been used to authenticate seafood with significantly greater accuracy and dependability in highly variable samples (Goyal et al., 2024).

6.5. Automation of Data Analysis

The limited limitations of spectroscopic methods and instrumental sensors can be overcome with continuing technological advancements in chemometrics software and computer science (Kharbach et al., 2023). Artificial intelligence and machine learning algorithms can be used to automate data analysis, which can eliminate the need for data analysis skills and increase the accessibility of spectroscopic methods to a larger variety of facilities (Mana et al., 2022).

6.6. Development of Portable Devices

It has been suggested that NSSEs can be further assisted by portable spectroscopic equipment and sensors, which can offer on-site analysis techniques (Yakes, 2022). The development of portable spectroscopic devices can make spectroscopic methods more accessible, especially in field-based settings. The use of portable spectroscopic instruments could lead to the quick and affordable detection of adulterants at any stage of the food manufacturing process (Moskowitza & Yakes, 2022). According to (Yang et al., 2024), portable spectroscopic devices are advantageous in terms of practical application. The rapid and on-site assessments of food products at different points in the food production chain are made possible by portable spectroscopic testing for food authentication (Moskowitza & Yakes, 2022).

6.7. Collaboration and Sharing of Data

In order to solve the inherent difficulties brought on by the international scope of the seafood business, global cooperation is essential in bolstering the effectiveness of enforcement systems (Yang et al., 2024). Collaboration between researchers and the sharing of spectral databases can improve the quality of calibration models, reduce the time and cost of developing new models, and advance the field of spectroscopic-based food authentication. In addition, collaborating and sharing data results in classification accuracy (Mizoguchi et al., 2022). Cooperation amongst countries, enabled by regulatory and intergovernmental bodies, is essential to developing a uniform enforcement framework. In order to overcome the jurisdictional and logistical challenges that come with the worldwide seafood trade, a united front against violations of traceability is made possible by this framework for international collaboration (Yang et al., 2024). Spectroscopic data analysis often involves the development of sophisticated chemometric models (e.g., multivariate analysis, principal component analysis, or partial least squares regression) to interpret complex spectra (Wang et al., 2022). While spectroscopic-based techniques offer advantages over traditional methods in terms of accuracy and speed, they can be more expensive to implement (Chaudhary et al., 2022). There is, therefore, a need for researchers and stakeholders to collaborate and share data so as to make spectroscopic-based techniques more accessible to the seafood industry (Bannor et al., 2023).

7. Conclusions and Future Directions

In the near future, researchers should study the integration of multiple spectroscopic-based techniques, which can improve the accuracy and reliability of results by providing complementary information. Also, the development of portable spectroscopic instruments should be looked at since it can make spectroscopic-based techniques more accessible to the seafood industry, enabling real-time testing in the field. Additionally, using genetic approaches combined with different spectroscopic techniques increases the accuracy of the results. In addition, the use of big data and machine learning algorithms, which can improve the accuracy and efficiency of spectroscopic-based techniques by enabling the analysis of large datasets and the development of predictive models, should be taken into consideration. Future research should focus on developing more accessible and cost-effective portable devices for real-time seafood authentication, ensuring broader industry adoption. While much of the research on spectroscopic-based techniques has focused on a few seafood species, there is a need to extend the application of these techniques to other seafood products to address the issue of food fraud and ensure the safety and authenticity of all seafood products.

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Author Contribution

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Conflict of Interest

The authors declare no conflict of interests.

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