**Review Article**

**Navigating Fishery Advancements with Fourier Transform Infrared Spectroscopy (FTIR)**

**Abstract**

The increasing demand for fish products worldwide, driven by increased awareness about the health advantages they offer, calls for improved techniques to ensure the safety, authenticity and quality of seafood. Fourier Transform Infrared Spectroscopy (FTIR) is a highly useful analytical method that provides valuable information about the molecular makeup of proteins, peptides, and other bioactive substances. It is widely used for protein profiling, species identification, heavy metal detection, and authenticity testing, offering reliable method to guarantee the integrity of seafood. This review explores the diverse applications of FTIR, highlighting its crucial role in the assessment and verification of fishery products. Food fraud, microbiological contamination, spoilage, and adulteration in fish and fish products are among the most serious issues that the technique may address because it allows for both qualitative and quantitative examination. FTIR is a quick and non-destructive tool that offers real time analysis, guarantees process optimisation, safety, and adherence to legal requirements. Additionally, the use of this technique in species identification and traceability helps to prevent fraudulent activities, preserving customer confidence and market integrity. As the fisheries sector evolves, FTIR continues to be at the forefront of sustainability and quality control initiatives, aligning with responsible practices and paving the way for the future of fisheries by delivering safe, high-quality and environmentally sustainable fishery products.

**Key words:** Fisheries, Fish protein, FTIR, Quality assurance

**Introduction**

Consumption of fish products has increased dramatically in recent years as a result of being recognised for its importance in healthy lifestyle and balanced diet (Coppola et al., 2021). With the increasing demand for fish consumption worldwide, the aquaculture industry plays a vital role for enhancing food security and fighting hunger. Fish is an affordable source of animal protein and a useful tool in the fight against malnutrition. Over the years, global fishing industry underwent a gradual evolution. In 2022, global fisheries and aquaculture production increased to 223.2 million tons and total fish production of India in the year 2022-23 is increased to 175.45 lakh tonnes with a contribution of 8.92% to world fish production. Fisheries sector is one of the key contributors of the country’s foreign exchange earnings and also plays an important role in the national economy. There is a growing demand for fish protein components, especially dried fish protein, for the production of functional foods in India (Handbook of Fisheries Statistics, 2023). Global demand for fish protein components, particularly fish protein powder is progressively rising as it is used as an ingredient in functional foods or ready-to-eat products. In line with the United Nations sustainable development goals, the aquaculture sector contributes significantly to improving food security and decreasing hunger (Ahmed et al., 2024). The essential amino acids found in fish and shellfish, as well as lipids high in polyunsaturated fatty acids, enzymes and other bioactive substances including vitamins and minerals, make them valuable food sources for humans. Seafood proteins can be separated and functionalized to create useful components for pharmaceutical and medical technologies, particularly for use in treating individuals with unbalanced and uncontrollable nitrogen levels (Hai, 2020). In terms of nutrition, fish and fishery products are great sources of protein and contain all the essential amino acids that are required for a healthy, well-balanced diet.

The last several decades have witnessed the emergence of Fourier Transform Infrared Spectroscopy (FTIR) as a reliable technique for characterising the structures of proteins and peptides. For the identification of organic compounds, infrared spectroscopy has long been a useful technique. It has gained popularity for the quantitative analysis of complex mixtures and the study of surface and interfacial phenomena (Dutta et al., 2017). Accurate and quick spectrum data collection is made possible by FTIR that permits simultaneous measurement of the whole spectrum (Fig 1). The overlay of the reference with the test sample elucidates the prominent changes (Fig 2). By measuring the absorption of infrared radiation across a range of wavelengths, this technique can be used to detect the functional groups found in both organic and inorganic molecules. FTIR spectroscopy is an affordable fingerprint approach that allows the sample to be simply placed on an Attenuated Total Reflectance crystal (ATR) without the need for sample preparation processes (Rohman et al., 2021). The FTIR method first generates an interferogram of a sample signal using an interferometer. Next, it applies a mathematical algorithm called Fourier transform to the interferogram to obtain the infrared spectrum. Thus, the interferogram is collected and digitalized by an FTIR spectrometer, which then applies the Fourier transform and spectrum is displayed. With solid, liquid, or gaseous materials, FTIR spectrometers may obtain infrared spectra in diffuse reflectance, transmission, transflection, ATR, specular reflectance and photoacoustic modes (Smith, 2011). Various sample handling techniques are summarized in table 1.

FTIR is a versatile analytical technique that can be used to assess a variety of materials, particularly those that are unknown (Dutta et al., 2017). It has been used to identify pure substances, impurities, mixtures and compositions of various materials (Pitucha & Kowalczuk, 2019; Pandey et al., 2016). In food analysis, it has become more significant, using the spectrum properties of the food matrix as a basis, it provides methods for both qualitative and quantitative food discrimination (Lohumi et al., 2015). With little or no sample pre-treatment, it can quickly, affordably, and non-destructively give both qualitative and quantit­­ative information about a food sample (Vargas et al., 2023). In the fisheries sector, FTIR has become an effective analytical instrument with various applications. It has been applied to a range of processes such as compositional evaluation, to identify whether fish is fresh or thawed, authentication, determining the geographical origin and identifying the type of provenance husbandry system. On laying emphasis on quality inspection, safety assurance and process optimisation, this review seeks to examine the various applications of FTIR in the fisheries sector.

**Table 1. Various Sample Handling Techniques (Verma et al., 2021)**

|  |  |
| --- | --- |
| **Technique**  | **Comments**  |
| **Attenuated Total Reflectance (ATR)**  | By generating an evanescent wave through total internal reflection, it is able to provide important molecular information through sample penetration. |
| **Diffuse Reflectance** | The basic concept behind its operation is the measurement of diffuse-reflected light, or reflected light that is produced when a sample partially absorbs light and then diffusely reemits it. |
| **Photoacoustic Spectroscopy**  | The mechanism involves analyzing molecules that absorb electromagnetic radiation and convert optical events into acoustic. |
| **Transmission** | An exact wavelength or frequency of light will be absorbed when infrared light enters the sample directly. |
| **Transflection** | Low cost substrates than transmission windows and a larger absorbance because the effective route length is nearly doubled when the same sample is passed through twice. |
|  **Specular Reflectance** | The surface of the sample may directly reflect the incident radiation concentrated on it, creating a specular reflection. |

In comparison to conventional techniques, FTIR exhibits a number of benefits such as

* Since sample preparation is not required, it is a non-destructive approach.
* Quick measurement and result delivery because the sample preparation stage has been omitted, making it very easy to conduct and reducing the likelihood of operator error.
* There are no chemicals employed in the procedure, it is an environmentally friendly analytical method.
* A single spectrum can be used to concurrently determine many of the material's constituent parts, allowing for the determination of physical as well as chemical properties of the sample.
* FTIR analysis precision is often high and accuracy is comparable to that of the chemical reference method.
* It can be applied to all light source frequencies, which speeds up analysis.



**Fig1.** The FTIR spectrum (% T Vs Wavenumber)

**Fig2.** Overlay spectra of test sample with the reference for comparison

**Applications of FTIR in Fisheries**

FTIR finds application in diverse ways within the fisheries sector and several of these applications are outlined below:



**Fig 3.** Summary of application of FTIR in fisheries

**For quality assessment of fish and seafood**

Ensuring food integrity from farm to fork is one of the world's critical issues today. Food adulterations driven by economic gain and issues with food authenticity are growing each day, having significant negative impacts on both health and the economy. With the use of efficient on-site food analysis tools, issues relating to food integrity could be detected and prevented (Cebi et al., 2023). Determining the proximate composition and assessing the freshness of products are two aspects of fish quality control (Liu et al., 2015). Fish species, sex, age, habitat, season, feed composition and environmental factors are the main determinants of the chemical makeup of fish meat. The protein level in fish meat is constant, but the ash and fat content varies. Proteins (16–21%), fats (0.2–25%), water (66–81%) and ash (1.2–1.5%), and make up the majority of the muscle in fish. Carbohydrates make up only 0.5% of the total composition and they are mostly stored in the liver and muscles as glycogen (Bagthasingh et al., 2016). It is possible to assess the freshness of whole fish by examining its eyes, gills, skin, and scales but determining the freshness of the fish after it has been filleted is not as easy. The quality of fish flesh is determined by two key elements i.e. chemical makeup and freshness (Hernandez-Martinez et al., 2013). High standards for process control and raw material quality assurance are necessary to meet the need for high levels of quality and safety in fish production. Fish loses quality and freshness due to the primary influence of native bacteria and their metabolic activity or quickly metabolized chemicals (Nie et al., 2022).

 The primary reason for fish discards during post-harvest handling, storage, processing, and distribution (sometimes referred to as post-harvest losses) is microbial activity. Under certain circumstances, such as temperature and time influences, that fish are exposed to after being caught, bacteria can proliferate and create metabolites. This may cause the product to lose quality and be rejected by the consumer's senses (Govari et al., 2021). Pathogenic bacteria have the potential to contaminate fish at every stage of production and processing the supply chain (Sheng et al., 2021). In addition to microorganisms, native enzyme activity and the oxidation of fish components may also cause fish to spoil under certain circumstances. Fish quality is greatly impacted by the detection of microbial growth and the management of microbial spoilage. Numerous techniques have been widely employed to assess the microbiological quality, such as microbial DNA analysis using polymerase chain reaction (PCR) or immunoassay-based techniques (Rahman et al., 2016). It should be mentioned that these techniques are time-consuming, difficult, some require high tech tools and unable to be used for the quick and non-destructive real-time detection of spoilage (Dourou et al., 2021). Important extracellular matrix components for fish fillet quality are detectible by FTIR spectroscopy (Sanden et al., 2019). In order to deal with the high moisture content in fish, FTIR spectroscopy uses a variety of techniques, including multivariate analysis methods like Partial Least Squares Regression (PLS-R) to create models that take into account the influence of water and extract useful data, data pre-processing techniques like smoothing and Standard Normal Variate (SNV) to fix scattering and baseline shifts caused by water absorption, and focussing on particular spectral regions less affected by water absorption. Despite the substantial amount of water present, FTIR can offer useful information on fish quality, composition, and possible adulteration by employing these techniques (Govari et al., 2021; Huang et al., 2018). FTIR is rapid, effective and non-invasive method for evaluating the microbial growth of fillets (gilthead sea bream) during refrigerated storage under Modified Atmospheric Pressure and aerobic conditions; this might therefore turn into a useful instrument to assess the quality of product in fish industry (Govari et al., 2022). In conjunction with chemometrics, it can be used to classify fish oils and predict the antioxidant activity of fish oils from various species and extraction techniques (Ikhsan et al., 2020). It could serve as a substitute for standard laboratory techniques used in the food industry for analysis (Benesova et al., 2022) and will reduce food waste, improving sustainability, welfare, and food security (Govari et al., 2021). The composition of fatty acids, in particular, plays an important part in determining the quality of fish meat. Infrared radiation is passed through a sample in FTIR, and the amount of radiation absorbed at various frequencies is measured. Fatty acids are among the several functional groups in molecules that absorb infrared light at specific frequencies. When combined with chemometrics (multivariate analysis), Fourier transform spectroscopy has demonstrated the potential to concurrently determine a variety of food product attributes including investigation of Trimethylamine (TMA) and dimethylamine (DMA) concentration during storage (Xu et al., 2022) with a small sample size, without the need for chemicals or labour-intensive sample preparation (Hernández-Martínez et al., 2013). Trimethylamine N-oxide (TMAO) is abundant in certain fish and seafood species and builds up in muscle to provide protection against pressure and cold. TMA and DMA are the by-products of degradation of TMAO during storage and could therefore be useful markers for assessing freshness. First, the origin spectrum was treated using the standard normal variable (SNV) spectral pre-processing approach, and dimensionality was reduced by using the successive projections algorithm (SPA). Second, two-dimensional infrared (2D-IR) correlation spectroscopy technology was used to evaluate the reasons behind the spectra produced by variations in squid freshness. Ultimately, chemometric techniques such as support vector regression (SVR), back-propagation artificial neural network (BP-ANN), and partial least-squares regression (PLSR) were used to estimate the freshness and make quantitative predictions of TMA and DMA (Xu et al., 2022). The speed and simplicity of use in daily operations are the primary benefits of this approach over conventional chemical and chromatographic methods. Furthermore, minimal to no sample preparation is needed for this technique (Fakayode et al., 2020). Based on several studies, summary of parameters analysed for quality assessment of fish and shellfish using FTIR are depicted in table 2.

**Table 2. Overview of recent studies that involved the use of FTIR for assessing the quality fish and shellfish**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sample**  | **Part**  | **Parameters analysed** | **Tool used** | **References**  |
| Atlantic Spanish mackerel, Crevalle jack, Atlantic bluefin tuna,  | Fish Fillets | pH, deterioration indices, chemical composition | FTIR + Partial Least Square (PLS) | Hernandez-Martinez et al., 2013 |
| Salmon  | Fillets  | Psychrotrophs, lactic acid bacteria, yeasts, molds*,* Brochothrix thermosphacta, Enterobacteriaceae, Pseudomonas, H2S producer counts | FTIR+PLS | Saraiva et al., 2017 |
| Sea bream | Whole ungutted fish | Microbiological spoilage | FTIR+ PLS | Fengou et al., 2019 |
| Gilthead Sea Bream  | Fillets  | Microbiological quality | FTIR+ PLS | Ryu et al., 2021 |
| Squid  | Squid meat | Trimethylamine (TMA) and Dimethylamine (DMA) | FTIR+ PLS, Support Vector Regression (SVR) and Back Propagation Artificial Neural Network (BP-ANN) | Xu et al., 2022 |

**Protein analysis**

Fish muscle is composed of approximately 16-21% protein and is very sensitive to high pressure treatment. The bulk of proteins in fish muscles are composed of stromal proteins (collagen), sarcoplasmic proteins (30%), and myofibrillar proteins (40–60%). Fish muscle proteins are more abundant in critical amino acids and readily digested than most meat proteins found on land. Essential amino acids include lysine, tryptophan, histidine, phenylalanine, leucine, isoleucine, threonine, and methionine are prevalent in muscle proteins. Consuming fish muscle protein has been linked to several health advantages, including antioxidant, antibacterial, and angiotensin-converting enzyme inhibitory properties (Ryu et al., 2021).

With a high degree of accuracy, the molecular weight of protein hydrolysates can be predicted using FTIR spectroscopy. Unlike X-ray crystallography and Nuclear Magnetic Resonance (NMR) spectroscopy (provide information on the tertiary structure), information regarding the secondary structure of proteins is obtained by FTIR spectroscopy. Infrared spectrum of every compound contains a unique collection of absorption bands. Amide I and Amide II are distinctive bands that are present in the infrared spectra of proteins and polypeptides. Absorption linked to the Amide II band predominantly causes bending vibrations of the N—H bond, whereas absorption linked to the Amide I band causes stretching vibrations of the C=O bond of the amide. Secondary structure content of protein can be determined by observing the Amide I and Amide II bands locations, as hydrogen bonding between the various parts of secondary structure involves both C=O and N—H bonds (Gallagher, 2009).

It is employed in industrial settings to monitor the sizes of proteins during enzymatic protein hydrolysis, opening the door for measurements of protein sizes in other applications (Kristoffersen et al., 2023), to investigate structural alterations in proteins, lipids and conformational structure of myofibrillar proteins, to detect, identify and assess the vibrations of certain bonds and functional groups linked to a distinctive molecular structure, FTIR spectroscopy is commonly regarded as pioneer technology because of its high sensitivity in identifying alterations in complex materials like tissues, bodily fluids, or cell structures, as well as in functional groups of tissue components including membranes, proteins, and nucleic acids (Karthikeyan, 2012). Additionally, this approach has a number of benefits, such as the capacity to analyse small sample volumes and evaluate the total composition of the sample concurrently. It eliminates the requirement for wet chemistry and requires only a basic sample pre-treatment (Guo et al., 2018). This technique is potentially applicable to find proximate composition in different tissues of fish (Umamageshwari et al., 2022) and to measure the sizes of protein during enzymatic protein hydrolysis (Kristoffersen et al., 2023). It has been shown that this technique, when paired with cluster analysis, may be a scientific tool for differentiating various surimi species in a comprehensive way (Bagthasingh et al., 2016). Based on several studies, summary of parameters studied for fish protein analysis using FTIR are depicted in table 3.

**Table 3. Overview of recent studies that involved the use of FTIR for analysis of fish proteins**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sample**  | **Part**  | **Parameters analysed** | **Tool used** | **References**  |
| Mrigal | Tissue  | Effect of heavy metals (Chromium and nickel) on tissue protein | FTIR | Karthikeyan, 2012 |
| Red tilapia  | Fillets  | Effect of cryoprotectant on red tilapia-based film.  | ATR-FTIR  | Oujifard et al., 2013 |
| Frozen hake | Muscle | Time and temperature history of fish muscle | FTIR | Careche et al., 2015 |
| Tilapia | Meat | Structural changes in surimi and tilapia fish protein isolate under different conditions | Raman spectroscopy and FTIR | Kobayashi et al., 2017 |
| Atlantic salmon | Muscle  | Physical changes and protein degradation | FTIR | Ovissipour et al., 2017 |
| Blue crab  | Meat | Impact of high-pressure processing on different protein fractions  | FTIR  | Martinez et al., 2017 |
| Grouper  | Fillets | Protein oxidation and degradation as a result of varying packing methods | FTIR  | Zhang et al., 2019 |
| Tilapia  | Fillets | Effect of Various Sous-Vide cooking conditions  | Synchrotron Radiation-based FTIR + PCA | Pongsetkul et al., 2023 |
| Tilapia | By-products | Differentiation of protein types | FTIR+PCA | Wachirattanapongmetee et al., 2024 |

**Heavy metal analysis**

As a result of metal pollutants building up in the tissues of different organisms and eventually bio-magnifying through the food chain, there has been an increase in awareness of these pollutants in the marine environment in recent years (Onyeabo, 2024). Unfortunately, the concentrations of heavy metals that are present in the environment naturally, especially the marine ecosystem, are substantially elevated due to the effects of industry, agriculture, effluents from the sewage and mining on the environment. Therefore, these metals can accumulate in aquatic organisms (fish, shellfish, and crustaceans) to potentially hazardous amounts (Djedjibegovic et al., 2020). Hence, before releasing sewage and effluent samples into water bodies, the necessary measures must be adopted to get rid of heavy metals (Rahman and Hassan, 2020). Evaluating the amounts of heavy metals in aquatic systems is crucial since many of them are hazardous even at low levels and persist in the environment long after the source has been eliminated. Numerous physical, chemical, and biological changes could occur from the release of heavy metal wastes into receiving waterways (Selmi et al., 2021). Since a significant portion of the chemicals used in industry, urbanization, and agriculture find their way into the marine and other aquatic habitats, aquatic environments are especially sensitive to harmful pollutants (Mustafa et al., 2024). Heavy metals in fish tissues can be identified and measured using FTIR in conjunction with suitable sample preparation methods. Crystallographic ionic bonds, covalent connections between atoms, and coordination bonds in metal complexes are excited by infrared light and a whole chemical makeup of the sample is reflected in the infrared spectrum that is produced (Quintelas et al., 2018). Metals dispersed in solution and heavy metals in sub-nanosized form or ionic cluster in a colloidal dispersed system can both be effectively characterized using the applied FTIR method. Information about the bonding, morphology, and oxidation state of the scattered clusters of heavy metal ions can be obtained from the infrared position strict control and calibration of sample treatment protocols. IR measurement methods, and IR acquisition parameters are necessary to achieve repeatable results by eliminating the noise (random variation) and keeping the principal components that capture the significant variation, chemometric models like analysis PCA and PLS (Mamera et al., 2020). Fish tissues can accumulate heavy metals as a result of absorption through the kidney, liver, and intestinal tract wall as well as along the gill surface to level higher than those found in the surrounding environment (Rajeshkumar et al., 2018). For determining the presence of heavy metals in river and borehole water sources, FTIR spectroscopy demonstrated promising results (Mamera et al., 2020). Being filter-feeding organisms, organic and inorganic substances easily enter in shellfishes. Heavy metals can build up in their bodies quite frequently, including Cd, Pb, Cu and Hg. Due to their widespread consumption in coastal areas, the presence of these heavy metals in shellfish poses a concern to human health and the environment. In identification of the structural arrangement of CaCO3 in shellfish and considering the potential use of waste materials for the absorption of metals, particularly heavy metals from contaminated water, FTIR provided the affordable structural information. FTIR spectroscopy helped in detection and reduction in the health risks associated with heavy metals by regulatory standards. Based on several studies, summary of the heavy metals detected in fish and shellfish using FTIR are depicted in table 4.

**Table 4. Overview of recent studies that involved the use of FTIR for detection of heavy metals in fish and shellfish**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sample**  | **Part**  | **Heavy metals detected** | **Tool used** | **References**  |
| Common carp (*Cyprinus carpio L*.), Silver carp (*Hypopthalmichtys molitrix V*.), Wels (*Silurus glanis L*.) | Liver | Effects of Cu2+ and Pb2+  | FTIR | Henczova et al., 2008 |
| Rohu *(Labeo rohita)* | Kidney  | Arsenic | FTIR | Palaniappan et al., 2009 |
| *Lates Calcarifer* | Muscle tissues | Nickel and Mercury  | FTIR | Senthamilselvan et al., 2012 |
| Oncorhynchus mykiss | Gills | Zinc, copper and cadmium | FTIR | Saibu et al., 2018 |
| Crayfish(*Astacus leptodactylus, Procambarus clarkii, Austropotamobius pallipes, Pacifastacus leniusculus, and Faxonius limosus*) | Cephalothorax exoskeleton | Cadmium, Lead, Nickel, Zinc, Chromium | ATR-FTIR | Volpe et al., 2020 |
| Seaweeds *(Gymnogongrus griffithsiae and Asparagopsis taxiformis)* | Seaweed | Arsenic, cadmium, copper, iron, mercury, potassium, manganese, sodium, phosphorus, and lead  | FTIR | Selmi et al., 2021 |

**Authentication and Species Identification**

The safety and eating quality of meat products are greatly influenced by their chemical makeup and microbiological characteristics, even though physical attributes including texture, appearance and colour are essential quality considerations at the time of purchase. Since fish and fish products are highly nutritious, there has been a significant growth in consumer demand for them over the past few decades. Because fish and seafood are perishable and have a high economic worth, this has led to an increase in commercial exchanges and import/export activities worldwide, which has escalated sanitary concerns and commercial frauds to improve prices, to substitute a product that is currently out of supply, to increase profits, or to add illegally caught fish to the legal food trade (Velez-Zuazo et al., 2021). Food provenance, authenticity, and traceability are growing global concerns for industry, government agencies, and consumers alike. Authenticity is an essential factor in ensuring adherence to specific standards or criteria. Furthermore, food security and safety are essential components of food quality, and in contemporary traceability and management systems, these concerns play a critical role. Customers need comprehensive and accurate information on the products they purchase and consume. Food is frequently adulterated, whether on purpose or accidentally, both with raw materials and finished goods (Cebi et al., 2023; Liu et al., 2015). This can result from mislabeling a product or from replacing a component with a less expensive or comparable one, which may ultimately lead to commercial fraud (Fox et al., 2018). The morphological characteristics of seafood species that allow consumers to differentiate one type from another are frequently lost during the preparation of seafood. Therefore, in the seafood industry, species replacement is a very common form of economic adulteration (Cawthorn et al., 2013). The relevance of food safety has grown over the past ten years as a result of rapid changes in the agro-food system (Ryu et al., 2021). Across the fish and fish product supply chain, the most prevalent frauds are selling frozen-thawed fish as fresh fish. A variety of analytical techniques, including electrophoretic, antibody, DNA and enzymatic approaches can be used to identify frozen items that are offered as fresh and species substitution. Unfortunately, these methods need highly competent operators and are time, money and reagent demanding. Spectroscopic techniques are rapidly gaining popularity because of its excellent specificity, ease of use and ability to be non-invasive, non-destructive and user friendly (Rady et al., 2018).

Vibrational spectroscopy is a widely used analytical method for assessing the quality of meat and meat products, together with other foods. Because it is able to perform multi-analyte assays and yield a wide range of data, FTIR spectroscopy which detects variations in molecules and produces sharp and narrow peaks in the mid-infrared region has become a non-destructive, quick, and easy method for assessing biological processes. Along with chemometrics, FTIR spectroscopy has been employed as a physicochemical fingerprinting approach in many kinds of food items for a number of reasons due to its speed, ease of use, and accuracy. FTIR spectroscopy has been applied to meat and meat products to investigate changes in chemical components such as lipids and proteins, assess microbial safety and shelf life, and identify adulteration (Candogan et al., 2021). FTIR can be used not only to authenticate raw fish and shellfish but also processed fishery products. Because of its unique characteristics, it could be utilised as a quick analytical technique for the identification of tuna fish oil with high accuracy (Irnawati et al., 2023) to study functional groups found in spiny lobsters (Kommuri et al., 2019), adulteration of *Salmo salar* with *Oncorhynchus mykiss* (Sousa et al., 2018) and analysis of milkfish oil (Mustafidah et al., 2021).

For the authentication and species identification of fish and seafood products, this technology is therefore a flexible and effective tool in fishery. Thus, the ability to quickly examine a large number of samples would improve consumer protection against adulterations and false claims (Sousa et al., 2018). Based on several studies, summary of authentication and species identification of fish, shellfish an oils using FTIR are depicted in table 5.

**Table 5. Overview of recent studies that involved the use of FTIR for Authentication and identification of fish and shellfish species**

|  |  |  |  |
| --- | --- | --- | --- |
| **Species**  | **Part**  | **Tool used**  | **References** |
| Atlantic mullet and red mullet | Fillets | FTIR | Alamprese et al., 2015 |
| Norwegian Salmon  | Whole fish | FTIR+ PLSDA (partial least squares discriminant analysis) | Wu et al., 2016 |
| Cod  | Liver oil | FTIR+PCA | Rohman et al., 2017 |
| *Pangasius micronemus* | Fish oil | FTIR + PLS and Principle component regression (PCR) | Putri et al., 2019 |
| Milk fish (*Chanos chanos*) | Fish oil (from head and flesh) | ATR-FTIR+PLSR | Mustafidah et al., 2021 |
| Tuna | Fish oil | FTIR-ATR | Irnawati et al., 2023 |
| Snakehead fish  | Fish oil | FTIR + Orthogonal projections to latent structures–discriminant analysis (OPLS-DA)  | Windarsih et al., 2023 |

**Detection of microplastics**

Microplastics are fibers and particles made of synthetic polymers that are less than a few microns in size. There are several ways they enter the environment. Due to their microscopic sizes, microplastics from personal care products and other sources are rapidly incorporated with municipal wastewater. During wastewater treatment plants, they are only partially removed before being released into aquatic environments. In addition, inefficient waste management, wind advection, atmospheric fallouts, and storm-water runoff are the main reasons of release of, microplastics into the environment (Mason et al., 2016). The traditional methods of detecting microplastics are gradually being replaced by spectroscopic techniques, where the potential of FTIR is recognized. It is crucial to carry out additional research in this field and investigate novel approaches for identifying and reducing the effects of microplastics in the environment (Mikulec et al., 2023). Based on their distinctive IR spectra, FTIR spectroscopy provides a means of accurately identifying plastic polymer particles. IR spectroscopy is the best method for identifying microplastics because plastic polymers have IR spectra that are extremely specialized and have recognizable band patterns (Choudhury et al., 2018). By capturing a progressive change of wavelengths, FTIR simultaneously gathers all wavelengths and processes the data using Fourier transformation to create a spectrum. The shift in the dipole moment results in an infrared spectrum, which is produced by FTIR. The characterization of microplastics has been done using various FTIR techniques, including micro-FTIR, which, unlike transmission FTIR, may be applied to thick or opaque samples and produces a high-resolution map of the sample (down to 20 mm) without the requirement for a preselection step; and attenuated total reflection FTIR (ATR-FTIR), that improves the information on irregular microplastics (Prata et al., 2019). Large microplastics are typically detached using tweezers and examined using ATR-FTIR. An attenuation wave is used to irradiate samples placed on an ATR crystal and large microplastics are identified and analyzed with speed and accuracy using this procedure (Dimassi et al., 2023). In sixty percent of the investigations, ATR-FTIR has been utilized to characterize distinct polymer types at varied environmental matrix conditions (Veerasingam et al., 2021). In aqueous samples containing large concentrations of biogenic organic matter, such as wastewater, FTIR imaging is a useful method for the precise and semiautomated detection of microplastics (Tagg et al., 2015). Aquatic ecosystems and the fish population can suffer major and negative consequences due to presence of hazardous compounds. In addition to identifying unknown elements, FTIR can assess quality and quantity of constituents of a sample. It can be utilised to detect microplastics in dolphins (Stockin et al., 2021), for Macroplastic and Microplastic analysis of aquatic and marine fish that can be used to assess the toxicity of the effluent in aquatic organisms (Rianda et al., 2008). Gram-negative, photosynthetic bacteria called cyanobacteria are able to produce blooms that are called harmful algal blooms (HABs) that eventually result in fish death. Environmental algal samples can be examined using FTIR to detect the presence or absence of potentially harmful cyanobacteria (Kenne et al., 2013) act as useful biomarkers for field evaluation in regions with a wide range of environmental parameters and an affordable tool in toxicological research (Senthamilselvan et al., 2014).‬‬ Based on several studies, microplastic polymers found in fish, shellfish, water and sediment are listed in table 6.

**Table 6. Overview of recent studies that involved the use of FTIR for identification of microplastic polymers found in fish, shellfish, water and sediment**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Sample** | **Sampling site** | **Part used** | **Microplastic polymer** | **Tool**  | **References** |
| Small Pelagic Fish | Mediterranean Sea | Digestive tracts | polyethylene terephthalate | FTIR | Lefebvre et al., 2019 |
| Zebra fish  | China Coastal Coast | Gut and gills | Polyester, polypropylene, polyethylene | FTIR | Su et al., 2019 |
| *Trichiurus sp. Johnius sp.* | Pangandaran Bay, Indonesia | Digestive tracts | Polyester | FTIR | Ismail et al., 2019 |
| *O.mossambicus, A. dussumieri, T. jarbua, Mugil cephalus,*  | South Africa | Tissue | Polyethylene, Polyester, Nylon, Polyvinyl Chloride  | FTIR | Naidoo et al., 2020 |
| Oyster *(Crassostrea gigas),* hard clam (*Meretrix lusoria)*, Loligo *(Loliginidae spp.)* | Taiwan | Whole animal | polypropylene, polyethylene, and polyethylene terephthalate | FTIR | Chen et al., 2020 |
| 158 fishes (16 species)  | Malaysia coastal waters | Gastrointestinal tract and gills | Polyethene, [polypropylene](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/polypropylene) , [acrylonitrile](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/acrylonitrile) [butadiene](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/butadiene) [styrene](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/styrene) , [polystyrene](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/polystyrene) and [polyethylene terephthalates](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/polyethylene-terephthalate)  | ATR-FTIR | Jaafar et al., 2021 |
| *Perca fluviatilis* and *Coregonus albula* | Lake Kallavesi, Finland  | Gastrointestinal tracts | Polyamide, polyester, polypropylene, polystyrene, PVC, polymethyl methacrylate, Acrylonitrile butadiene styrene | Imaging FTIR  | Uurasjärvi et al., 2021 |
| Sufflamen fraenatus, Heniochus acuminatus, Atropus atropos, Pseudotriacanthus and Leiognathus brevirostris) | Gulf of Munnar (Indian Ocean) | Muscle and intestine | **Muscles:** Polyethylene, polypropylene, polyamide and fiber and **Intestine:** polyamide, polyethylene, polypropylene, and fiber  | Micro-FTIR | Selvam et al., 2021 |
| Fish and shellfish | Sundarbans | Muscle and gastrointestinal tract  | **Muscle:** Polypropylene, polypropylene, Polyamide, **Gastrointestinal tract:** Polypropylene, polypropylene, ethylene vinyl acetate | ATR-FTIR | Sultan et al., 2023 |
| Fish *Dicentrarchus labrax*, *Sparus aurata*, Mussel (*Mytilus galloprovincialis*), and Water Samples | Northern Ionian Sea | **Fish:** Gastrointestinal tracts and **Mussel:** Tissue and water | Polyethylene, polyethylene-co-vinyl acetate, polyvinyl-butyral, polyvinyl alcohol, and polybutyl methacrylate | ATR-FTIR | Miserli et al., 2023 |
| Water, sediment, and fish | Martapura River | Water, sediment, and fish | Nylon, polystyrene and polycarbonate | FTIR | Annisa et al., 2024 |

**Chemical composition of fish**

Compared to other animal proteins, fish is an affordable and easily digestible source of protein. In addition to containing proteins, carbs, lipids, vitamins, and trace elements, fish is a major source of essential fatty acids (Sumi et al., 2016). Protein, fat, ash, and water are the main components of fish meat and are usually employed as indicators of the nutritional value of fish. In general, these components vary according to species, feeding habits, migration patterns, age, size, sex, environment, or season (Mocanu et al., 2022). A processing technician may determine the best processing and storage conditions with the aid of information on the biochemical constituents, ensuring the highest possible degree of quality preservation. A crucial tool for explaining food safety issues is the assessment of quality indicators. The vitamin and mineral contents of the fish are also important for the metabolic alterations that occur in the fish after death. It is essential to understand the chemical makeup of fish species in order to assess the quality of raw materials, storage stability, and technical procedures. The quality of fish is indicated by its biochemical and mineral content. Using multivariate calibration techniques, an additional technique for determining the quality attributes of meat and meat products is Fourier transform near infrared (FT-NIR) spectroscopy (Velez-Zuazo et al., 2021). The combination and vibration overtones of the fundamental O—H, C—H, S—H, and N—H bonds are the primary observable phenomena in the NIR region (750–2500 nm). The wealth of information gained and the ability to ascribe specific absorption bands to its functional groups, including these hydrogen bonds, are the main reasons of importance of NIR spectroscopy for identifying molecular structures. Because of the abundance of information it yields and the ability to link certain absorption bands to functional groups, such as these hydrogen bonds, NIR spectroscopy is crucial for identifying molecular structures (Ma et al., 2019). FTIR can be used to determine proximate composition of fish and makes it simple to identify the main biological components, such as proteins, carbohydrates, and lipids and is capable of being used as an analytical tool to detect and monitor structural and functional changes in physiology of fish. Furthermore, it offers a quick and easy way, independent of histopathologic data or blood parameters, to identify physiologic alterations resulting from any histopathologic state (Ceylan et al., 2014). The conventional techniques for determining fatty acids include extracting fat, converting it to its methyl ester, and then analysing the result using gas chromatography (GC). This analysis produces hazardous wastes in addition to being costly and time-consuming. Therefore, it is ideal to develop an analytical technique for fish quality assessment that is quick, affordable, reliable, and environmentally friendly and does not rely on chemical assays and these characteristics are typical of Fourier transform infrared spectroscopy techniques. Good estimates of total fat, fatty acid groups, specific fatty acids, and nutritional factors can be obtained using this technique. The primary benefits are the ability to predict outcomes in 10 minutes as opposed to hours when employing traditional chromatographic and chemical techniques, with no preparation, just a small quantity of sample, no reagents, and no harmful waste generated (Hernandez-Martinez et al., 2013). Based on several studies, summary of parameters analysed for measuring chemical composition of fish and shellfish are depicted in table 7.

**Table 7. Overview of recent studies that involved the use of FTIR for measuring chemical composition of fish and shellfish**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Species** | **Part** | **Parameters** | **Tool used** | **References** |
| Fish oil | Micro-encapsulated fish-oil supplements | Fatty acid compositions | ATR-FTIR+ PLSR | Vongsvivut et al., 2012 |
| Tunas, striped bonito, fin-fish hoki, Sharks | Marine oils | Polyunsaturated Fatty Acid Composition | ATR-FTIR+ PCA | Vongsvivut et al., 2012 |
| Atlantic Spanish mackerel, Atlantic bluefin tuna, crevalle jack, | Fish fillets | nutritional parameters, fat content, fatty acid composition  | MID-FTIR | Hernandez-Martinez et al., 2013 |
| Cuttlefish (*Sepia pharaonis)* |  Mantle  | Moisture, ash, lipid, and carbohydrates | FTIR | Kavipriya et al., 2014 |
| *Heteropneustes fossilis*  | Gills, liver, intestine, muscle and ovary | Carbohydrate, Protein, Lipid, Moisture and Minerals | FTIR | Umamageshwari et al., 2022 |

**Limitations**

Even with the increasing number of researches in this field, there are still certain issues with FTIR spectroscopy that need to be resolved before this method can be applied on a regular basis. One significant limitation is its sensitivity, since the method is surface-sensitive; obtaining a spectrum of high quality requires good contact. The efficiency of the ATR-FTIR technique is determined by the quality of contact between the ATR sensing surface and the sample, as the evanescent wave can only penetrate a material up to a distance of 4-5 μm (Vongsvivut et al., 2012) for a diamond ATR crystal). The metabolic profiles detected by FTIR can be influenced by external factors like temperature and handling conditions, making it more difficult to interpret results pertaining to fish welfare and stress reactions (de Magalhaes et al., 2020).

Low spectral quality can be caused by inadequate contact, which will lower the accuracy of method. The sample thickness issues may cause systematic spectral shifts, CO2 interference, and the possibility of the analysis being destructive if the sample is subjected to excessive pressure and it may harm the ATR crystal surface. A potential drawback of using ATR-FTIR for virus detection is the potential for spectral band overlap between the virus and the host cell. There will be peaks in the 1800–900 cm−1 regions that correspond to proteins and genetic material; however, since these biochemical structures are present in both cells and viruses, spectral band overlap is expected and this may make discrimination challenging (Santos et al., 2020). Multiple background scans as well as sample scans are required to prevent spectral variations due to surrounding environmental conditions in sample heterogeneity. The FTIR spectra of the sample, for instance, may change when it is measured in culture media at different temperatures. Pre-treatment of the samples may be necessary in order to purify them and prevent overlapping peaks on the spectra (Eid et al., 2022). The reliability of the results may be impacted by noise introduced into the spectral data by variations in sample preparation. To reduce this noise, thorough reference databases and improved sample handling are required (Goldstein et al., 2021). Despite these challenges, FTIR spectroscopy holds significant potential for enhancing data collection in fisheries research. In order to maximise the use of FTIR in this field, these problems must be addressed by enhanced calibration models, noise reduction strategies, and validation studies.

**Conclusion and future prospects**

FTIR is an essential analytical instrument in the fishing industry that provides a thorough approach to sustainability, safety assurance and quality assessment. From protein analysis to species identification, contaminant detection and real-time freshness monitoring, FTIR's versatility addresses key challenges in the industry. Its importance to sustainable practices is further highlighted by its role in quality assessment and heavy metal analysis in aquaculture. FTIR is an essential tool as the fishing industry develops, supporting responsible practices, guaranteeing product quality and encouraging research breakthroughs. The fish industry uses it as a useful tool to assess product quality, which lays the foundation for using FTIR as an industrial tool for product and process management and optimization. Promising strategies for effectively and consistently enhancing traceability along the food value chain in the direction of sustainability include adapting and utilizing advanced technologies. Researchers and the industry will be able to advance and create innovative applications which can address the best management practices in the processing, manufacturing, and marketing of food products and raw materials.

But a number of hurdles continue to stand in the way of FTIR's expansion and advancement in the fish and seafood sectors. Additionally, the majority of training programs and courses offered today still emphasize the so-called classical approach, which leaves out a number of factors connected to new technology. The industry is becoming more and more interested in rapid analytical techniques, even though traditional methods such as sensory, physicochemical, rheological, and others have been used to evaluate the quality of fish and seafood products. This is especially true when it comes to sample conservation, costs and time (as non-invasive and non-destructive methods of analysis are preferred). FTIR holds the potential to reshape the future of fisheries, aligning with the industry's commitment to delivering safe, high-quality and environmentally sustainable fishery products.

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* Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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