

A Review on Recent Advances in Imaging Technologies for Quality and Safety Assessment of Fish and Fishery Products

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ABSTRACT

Fish and fishery products are an important source of protein, essential omega-3 fatty acids, and micronutrients. However, they are prone to rapid spoilage via autolysis, lipid oxidation, and microbial proliferation, necessitating sophisticated quality assessment techniques. Traditional sensory and chemical tests (e.g., TVBN, K-value, TBARS) are destructive, lengthy, and unsuitable for high-throughput applications. This review examines imaging technologies like computer vision (RGB), multispectral/hyperspectral imaging (HSI), VIS/NIR spectroscopy, and UV/fluorescence imaging as non-destructive alternatives for assessing fish product freshness, composition, defects, safety, and authenticity. Key principles include image acquisition, preprocessing, feature extraction (color, texture, spectra), modeling using chemometrics (PCA, PLS, SVM), and deep learning (CNNs, transformers). Applications involve automated grading, spoilage prediction (e.g., eye/gill changes, spectral freshness indices), moisture/fat mapping, bruise detection, parasite detection, and process monitoring. These systems can be integrated with E-Nose and AI for online industrial use, helping to minimize waste and improve traceability. Challenges include cost and calibration; prospects include miniaturized hardware and multimodal fusion for sustainable seafood processing.

1. INTRODUCTION

Fish and fish products are good sources of high-quality protein, long-chain omega-3 fatty acids, and micronutrients. They have been consumed more widely as a result of the growth in capture fisheries and aquaculture. However, the high-water content, readily soluble nitrogenous compounds, and

oxidizable lipids of fish muscle cause rapid deterioration. This deterioration is due to autolysis, lipid oxidation, and microbial spoilage that occur during handling and storage (Patel et al., 2024; Sun et al., 2024). The lack of good management practices can result in high economic costs and food safety issues, as well as food waste in domestic and export seafood markets. Traditional methods of evaluating fish

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quality and freshness include sensory assessment of appearance, odour, and texture, and laboratory parameters such as TVB-N, K-value, pH, TBARS, and microbial counts (Patel et al., 2024; Sun et al., 2024). While these traditional techniques are reliable, they are destructive, tedious, time-consuming, and expensive. They are especially not suited for high-throughput online inspection. Furthermore, sensory panels are subject to inter-assessor variability and assessor fatigue (Patel et al., 2024; Saha and Manickavasagan, 2021).

These limitations have led to the development of "artificial sensing" technologies that combine imaging, spectroscopy, and advanced data analysis to measure fish freshness and safety in a fast and objective manner without altering the fish's quality (Sun et al., 2024; Saha and Manickavasagan, 2021). In the last 20 years, a variety of optical imaging techniques have been used, from basic RGB computer vision to multispectral imaging (MSI), hyperspectral imaging (HSI), and UV/fluorescence imaging, to quantify surface and internal quality attributes of fish and fishery products (Sun et al., 2024; Patel et al., 2024). Most computer vision platforms analyze and interpret colour, texture, and geometry aspects related to freshness and visible flaws (Ozdogan et al., 2021). However, VIS/NIR spectroscopy and HSI associate pixel-by-pixel spectral data with moisture, fat, protein levels, and biochemical markers (Sun et al., 2024; Patel et al., 2024; Ozdogan et al., 2021).

Subsequently, freshness indices have been developed and integrated into a single index, and spatially resolved quality maps have been created for species such as salmon and mackerel. These advances indicate that, in many cases, information derived from non-destructive imaging can be as good as information derived from traditional laboratory analysis, with great potential for supporting decision-making (Yu et al., 2021; Sun et al., 2024). The performance and robustness of imaging-based quality assessment have been further enhanced by recent advances in machine learning, particularly deep learning (Saha and Manickavasagan, 2021; Pu et al., 2023). Convolutional neural networks (CNNs) and compact CNN models, such as MobileNetV1 models with attention modules, and newer transformer-based CNN models, have proven very successful in predicting freshness categories from images of eyes, skin, and fillets, and in distinguishing species and/or product classes from multispectral or hyperspectral images (Sun et al., 2024; Pu et al., 2023). Moreover, combining image information with electronic noses or environmental sensors in multimodal fusion has enhanced early detection of quality deterioration. This allows for more robust and non-destructive

monitoring in realistic storage and distribution environments (Sun et al., 2024; Pu et al., 2023). Consequently, image systems have moved from laboratory demonstrations to pilot-scale and industrial uses such as online grading, automatic defect detection, and process supervision in seafood processing plants (Patel et al., 2024; Sun et al., 2024).

This review emphasizes the principles and latest developments in the use of imaging technologies to assess the quality of fish and fishery products. It includes computer vision, multispectral imaging, hyperspectral imaging, fluorescence imaging, and UV imaging, and how they can be combined with chemometrics and artificial intelligence to evaluate freshness, composition, safety, and authenticity

2. PRINCIPLES OF IMAGING-BASED ASSESSMENT

Imaging systems can take a 2D or 3D picture of a fish or a fish product with the help of reflected, transmitted, or emitted radiation from the product, which can be in the visible and NIR range (Sun et al., 2024; Patel et al., 2024). Classical computer vision systems are based on obtaining morphological and color characteristics from RGB or grayscale images, while HSI systems and MS imaging systems obtain a spectrum of information per pixel that can be correlated with the chemical composition of the image and the spatial distribution of the image element (Sun et al., 2024; Ozdogan et al., 2021). Typically, image analysis begins by preprocessing the image to remove noise and correct the colour. Then, it moves on to segmentation (separating fish from the background image), feature extraction (colour, texture, shape, spectral bands), and multivariate modelling (PCA, PLS, SVM, CNNs) to predict quality attributes and/or classify freshness and defects (Saha and Manickavasagan, 2021; Sun et al., 2024).

3. PRINCIPLES OF IMAGING-BASED ASSESSMENT

3.1. Computer and machine vision (RGB/2D imaging)

Machine vision is a technique that relies on digital cameras, lighting, and image processing algorithms to assess external features like size, shape, colour, surface defects, bruising, and gapping in fish and fillets (Liyanage et al., 2024; Zheng et al., 2026). Initial grading and sorting systems, and later systems, use colour and texture changes on the skin, eyes, and gills to estimate body weight, species, and freshness (Liyanage et al., 2024; Zhang et al., 2022). Some of the

key applications include Automated grading of whole fish based on length, volume, and body shape, often used at farm or plant level as a non-contact alternative to manual weighing; Estimation of freshness via regression models using colour parameters obtained from skin or fillet images, or features derived from the skin or fillet images (Liyanage et al., 2024) and checking for defects to support quality-based trimming and sorting (like blood spots, bruises, parasites, melanosis, gaping) (Zheng et al., 2026). Recent methods combine deep learning architectures like MobileNetV1 with attention mechanisms to categorize fish freshness using images, outperforming conventional handcrafted feature approaches with high accuracy and robustness (Zheng et al., 2026; Yildiz et al., 2024). The low cost of cameras and embedded hardware has also made it possible to have portable and online machine-vision systems for small- and medium-scale processors (Liyanage et al., 2024; Zheng et al., 2026).

3.2. Visible/NIR spectroscopy and imaging

The second type is VIS/NIR spectroscopy using diffuse reflectance or transmittance spectra and is widely used to estimate intrinsic quality attributes (moisture, protein, fat, and salt content) in fish (Sun et al., 2024; Patel et al., 2024). These systems can be combined with imaging (NIR or VIS-NIR HSI) to give quantitative prediction and spatial maps of composition over fillets and over whole fish (Sun et al., 2024; Ozdogan et al., 2021). Important applications include (1) Proximate analysis (moisture, fat, protein) of fillets to support grading by nutritional value; (2) Adulteration and mislabelling (species substitution, fresh vs. frozen/thawed fillets, organic vs. conventional salmon) detection (Patel et al., 2024; Ozdogan et al., 2021) and (3) chemometric classification models based on spectral signatures (Saha and Manickavasagan, 2021). VIS-NIR HSI was used to map the drip loss and pH distribution in Atlantic salmon fillets, enabling the visualization of heterogeneity related to texture and yield (Sun et al., 2024; Patel et al., 2024). The interest in online industrial application has increased due to the benefits of online NIR-HSI, that includes rapid measurement, little or no sample preparation, and simultaneous detection of multiple quality attributes (Sun et al., 2024; Patel et al., 2024; Ozdogan et al., 2021).

3.3. Hyperspectral imaging (HSI)

HSI is performed by acquiring a continuous spectrum of information for every pixel, across tens to hundreds of narrow bands in the 400-700 nm range (Sun et al., 2024; Patel et al., 2024). Fish Quality Assessment (FQA) has been especially effective in

simultaneously assessing chemical composition, physical properties, freshness indices, and food safety parameters in fish (Sun et al., 2024; Pu et al., 2023). Its applications include: (1) The application of VIS/NIR HSI to freshness evaluation of sardines in chilled storage as the freshness progresses was illustrated by the PCA of hyperspectral data distinguishing the samples during the different storage times (Sun et al., 2024; Hardy et al., 2024); (2) Generation of regression models for the prediction of moisture content, fat-related compounds, textural characteristics, and freshness indices from HSI data ($R^2 > 0.80$), which allows quantitative mapping of those traits (Patel et al., 2024; Sun et al., 2024); (3) Process monitoring: monitoring by measuring the change in the spectrum related to the change in structure and moisture (Process changes (thermal processing, freezing, dehydration), spectral changes tracking) (Sun et al., 2024; Pu et al., 2023) and (4) Optimal selection of wavelengths and chemometrics for food safety evaluation (detection of surface defects, faecal contamination, parasites, and, in some cases, microbial spoilage marks) (Patel et al., 2024; Sun et al., 2024). Finfish fillet inspection systems have been developed for the fish market under EU projects like SPECTRAFISH, which offer significant benefits: non-invasiveness, automated operation, high speed for integration with fish processing lines, and visualization of spatial distributions of several quality and safety parameters (Sun et al., 2024). These efforts demonstrate the possibility of achieving full quality inspection on an industrial production line in real time by integrating HSI (Sun et al., 2024; Patel et al., 2024).

3.4. Fluorescence, UV imaging and specialized modalities

Fluorescence and UV imaging rely on the light emitted by the fish surface when excited by a certain wavelength, which is due to reaction products or endogenous fluorophores, and enable high sensitivity to biochemical changes related to fish spoilage (Sun et al., 2024; Pu et al., 2023). In the case of whole fish, a machine-vision system with UV light at 365 nm was used to determine colour parameters (a^* , b^*) using fluorescence images, and a high correlation with aerobic plate counts ($R^2 \approx 0.97$) was found, indicating the capability of the machine as a rapid freshness indicator (Pu et al., 2023; Patel et al., 2024). These are complemented by other modalities such as front-face fluorescence spectroscopy integrated with an imaging unit, which allows the detection of early signs of spoilage and quality changes with high sensitivity to protein and lipid oxidation products (Pu et al., 2023); thermal or infrared imaging for detection of temperature heterogeneity, cold chain abuse, and surface dehydration, which indirectly influences

quality and shelf life (Sun et al., 2024); and 3D or stereo imaging for volume and shape measurement, supporting weight estimation and yield prediction in processing (Sun et al., 2024; Patel et al., 2024). Some of these methods are still in the research phase, but they can be used in conjunction with RGB or HSI systems and will reduce the scope to focus on a particular biochemical or physical phenomenon (Sun et al., 2024; Pu et al., 2023).

4. IMAGING APPLICATIONS TO KEY QUALITY ATTRIBUTES

4.1. Freshness and Spoilage

The most important quality attribute is freshness, which is evaluated with a sensory scheme, K-value, TVB-N, or microbial counts (Liyanage et al., 2024; Patel et al., 2024). Imaging technologies are able to remotely detect spoilage-related deterioration in colour, gloss, texture, and sometimes fluorescence, which allows for the estimation of freshness indices and remaining shelf life (Sun et al., 2024; Liyanage et al., 2024). Some examples are:

- RGB images processed to extract colour and texture features, which were used to train and test supervised learning models for fish freshness classification (Yildiz et al., 2024; Liyanage et al., 2024).
- Eye and gill region segmentation and analysis algorithms based on computer vision to estimate freshness based on colour and structure changes in fish during ice storage (Liyanage et al., 2024).
- HSI-based models that predict TVB-N, K-value, and microbial counts in fish with R^2 values of > 0.85 , which are adequate for fast screening of fish freshness (Sun et al., 2024; Hardy et al., 2024).
- Surface colour parameters that can be used to accurately predict the microbial load through the use of UV fluorescence imaging systems, providing real-time predictive microbial monitoring (Pu et al., 2023; Patel et al., 2024).

These technologies involve online sorting of fresh fish, optimization of the cold chain process, and waste reduction resulting from improved shelf-life management (Sun et al., 2024; Patel et al., 2024; Liyanage et al., 2024).

4.2. Composition and Nutritional Quality

Imaging systems, especially NIR and HSI, can efficiently predict proximate composition and related nutritional properties (Sun et al., 2024; Zuo et al., 2025). Water, lipid, protein, and salt in cured products

are related to spectral data, which can be correlated to enable non-destructive grading by fatness and nutrition (Zuo et al., 2025; Patel et al., 2024). Quantitative prediction of moisture, protein, and fat contents in salmon fish fillets using VIS/NIR and NIR-HSI has been demonstrated, in which the error of the quantitative prediction has been proved to be reliable for use in industrial screening (Luo et al., 2023; Sun et al., 2024); mapping of the fat distribution for salmon fillets, which is relevant to fish quality consistency, sensory properties, and fish process behaviour (Luo et al., 2023; Patel et al., 2024); and monitoring moisture and mass changes in the fillets of vacuum freeze-dried grass carp using NIR-HSI, which is used to obtain information about the fish drying kinetics and process optimization (Duan et al., 2025; Sun et al., 2024). Some of these features enable processors to maintain product uniformity, fine-tune process details such as salting, smoking, and drying, and ensure accurate product labelling for consumers (Zuo et al., 2025; Sun et al., 2024; Patel et al., 2024).

4.3. Defects, Safety, and Authenticity

Imaging plays an essential part in the detection of visual defects, in safety assurance, and increasingly in authenticity verification (Sun et al., 2024; Pu et al., 2023). Applications include:

- Detection of visible defects (bruises, blood spots, gaping, parasites) in fillets by using an RGB or HSI system, which allows for automated trimming or rejection (Zheng et al., 2026; Liyanage et al., 2024).
- Detection of surface contamination and foreign materials by using spectral and color differences, especially in the HSI system used for hygiene inspection (Patel et al., 2024; Sun et al., 2024).
- Discrimination between fresh and frozen/thawed fish, and between wild and farmed or organic and conventional fish by using the NIR-HSI system and chemometric classification models, at the fillet level (Patel et al., 2024; Ozdogan et al., 2021).

Imaging eliminates the need for destructive lab analysis and provides quick screening for defects and authenticity to enhance quality control throughput (Sun et al., 2024; Patel et al., 2024; Zheng et al., 2026).

4.4. Process Monitoring and Online Control

The use of imaging technologies for closed-loop control and monitoring of fish processing lines is growing (Sun et al., 2024; Patel et al., 2024). VIS-NIR HSI has been used to assess the effect of thermal processing and freezing by mapping changes in

textural and moisture content, which has facilitated process control of thermal processing and freezing (Sun et al., 2024; Pu et al., 2023). Machine-vision systems at the grading line measure size and weight to ensure the best possible filleting, cutting, and packing, and ensure the required customer specifications are met (Liyanage et al., 2024; Zheng et al., 2026). Online inspection of cod and salmon fillets is feasible, as is the automated acquisition, model-based prediction, and visualization of the distribution of multiple attributes at line speeds, as shown by industrial prototypes like the SPECTRAFISH HSI system (Sun et al., 2024). Such systems look towards future smart factories equipped with digital twins as well as quality-driven process optimization, with imaging data feeding into these (Sun et al., 2024; Patel et al., 2024; Zheng et al., 2026).

4.5. Data analysis, Chemometrics, and AI

Because of the dimensionality of both spectral and spatial data, advanced data analysis is needed for effective use of imaging for quality assessment (Saha and Manickavasagan, 2021; Sun et al., 2024). Traditionally, chemometrics (such as PCA, PLS, LDA, or SVM) has been used to reduce the dimensionality of image data and to build calibration models that relate the image data to reference measurements (Saha and Manickavasagan, 2021; Patel et al., 2024). Deep learning, especially convolutional neural networks (CNNs), for feature learning and classification from RGB or hyperspectral images is a recent trend, which is much more robust to illumination and sample presentation variation (Zheng et al., 2026; Sun et al., 2024). Other developments include hybrid models that incorporate image features and the results of other sensors (such as electronic nose, physical variables), and intelligent inference systems such as fuzzy logic and adaptive neuro-fuzzy inference systems (ANFIS) to deal with uncertainty in quality assessment (Pu et al., 2023; Zheng et al., 2026). Furthermore, multisource data fusion, which combines imaging, spectroscopy, and traditional measurements, is being exploited to create holistic fish freshness indices for species such as salmon (Yu et al., 2021; Sun et al., 2024). These developments all contribute to improving predictive performance and bring imaging systems closer to becoming fully automated decision support tools in quality and safety management (Sun et al., 2024; Patel et al., 2024; Zheng et al., 2026).

5. ADVANTAGES, LIMITATIONS, AND PROSPECTS

There are several advantages of imaging technologies over traditional approaches: they are

fast, non-destructive, automated, and can capture both spatial and spectral data, which means multiple quality attributes can be evaluated simultaneously (Sun et al., 2024; Patel et al., 2024). In an industrial setting, they eliminate reliance on labour-intensive sensory inspection and destructive laboratory testing and allow higher sampling rates and more consistent quality control (Patel et al., 2024; Zheng et al., 2026). However, some challenges persist, such as limits on adoption due to high capital cost and complexity, particularly for HSI systems (Sun et al., 2024; Patel et al., 2024). Robust reference data must be developed for calibration and validation, including industrial variability (species, batches, seasons, processing conditions) (Patel et al., 2024; Pu et al., 2023); processing, maintenance, and integration of these models with plant information systems are important when dealing with large quantities of data (Sun et al., 2024; Zheng et al., 2026); transferring models between instruments and sites is still a practical challenge (Patel et al., 2024; Sun et al., 2024).

Future directions involve the miniaturization of imaging hardware, development of low-cost multispectral systems for specific tasks, wider application of edge AI with real-time analysis, and better integration of imaging with other sensing modalities (electronic nose, biosensors) for smart quality management systems (Sun et al., 2024; Zheng et al., 2026). Imaging technologies are poised to play a key role in the digitalization and sustainability of fish and seafood value chains and are likely to be essential to advancing quality, safety, traceability, and waste reduction (Sun et al., 2024; Patel et al., 2024; Zheng et al., 2026).

6. CONCLUSIONS

Imaging technologies are changing the way fish and fishery products are assessed in terms of quality, moving from subjective and destructive assessment to fast, objective, and nondestructive monitoring. Optical and intelligent sensing approaches have gained increasing importance because they enable rapid, real-time, and non-destructive evaluation while reducing labour requirements, analysis time, and operational costs while traditional methods such as sensory assessment, microbial analysis, TVB-N, K-value, and other biochemical measurements are still crucial. RGB machine vision is an effective and low-cost method for grading, defect detection, and freshness assessment. Both VIS/NIR spectroscopy and hyperspectral imaging correlate spatial and chemical information, as well as spoilage. The detection and analysis of specific biochemical or physical phenomena associated with quality deterioration are accomplished by using

fluorescence, UV, thermal, and 3D imaging. The combination of these modalities with chemometrics and AI, particularly deep learning, has greatly enhanced the accuracy, robustness, and automation of predictions. Imaging systems can provide good estimates of freshness, moisture distribution, fat distribution, defect and contamination detection, authenticity, and real-time processing monitoring. Their industrial applications are increasing, especially in the field of online grading and smart quality control in seafood processing. Challenges include equipment cost, transfer of calibration, data handling, validation of models under industrial variability, and widespread use by small-scale processors. Advancing to the next steps of the future will entail miniaturized multispectral devices, real-time analysis using edge-AI tools, multimodal sensor fusion, cloud-based quality platforms, and digital traceability integration. These will help in reducing waste, ensuring consistency, ensuring food safety, and empowering data-driven decisions in the seafood value chains, supporting sustainable seafood. Advanced imaging technologies coupled with AI and chemometric analysis are becoming an integral part of next-generation intelligent fish quality management systems. Future development and industrialization will play a key role in enabling safer, efficient, and sustainable fisheries and seafood processing.

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