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Applications of Multispectral Imaging for Rapid Detection of Food Adulteration

Yunlai Cai

College of Chemistry and Chemical Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi, 710600, China

ABSTRACT
The adulteration of food has become a global problem and a regular source of concern to food quality and safety. Traditional laboratory methods for detecting fraud and contaminants are often time-consuming and destructive, creating demand for rapid, on-site analytical techniques. Multispectral imaging technology, as a promising method, could be employed to fast and non-destructively identify food adulteration. This work presents a review on the principles of multispectral imaging and examines its applications across various food categories, including dairy and liquid products, powdered and plant-based products, and meat and seafood. Case examples from recent studies illustrate how multispectral imaging can reveal subtle adulteration that might evade conventional inspection. This work also considers the potential of this technology to enhance authenticity verification in the food industry and integrate into modern quality control practices. The paper concludes by addressing current challenges and prospects for deploying multispectral imaging in routine food monitoring.

KEYWORDS
Multispectral imaging; Food adulteration; Rapid detection; Food authenticity; Non-destructive analysis

1 Introduction

Adulteration of food products, whether by diluting with inferior materials, substituting ingredients, or adding harmful additives, is a longstanding problem that undermines consumer trust and health. Industry estimates suggest that food fraud costs the global sector tens of billions of dollars each year, providing a strong incentive for better detection technologies. High-profile scandals, such as the addition of melamine to milk powder or the substitution of horse meat for beef in commercial products, have underscored the need for improved methods [1]. Beyond these incidents, everyday economic adulteration continues to affect supply chains worldwide. Regulators and food producers rely on testing to ensure authenticity and safety, but conventional analytical techniques are laborious, require laboratory facilities, and destroy the sample. This creates a powerful incentive for rapid, non-destructive testing approaches that can be deployed in the field or on production lines.

These non-laboratory methods are already proving effective in practice. For example, Zhang et al. (2025) used a handheld near-infrared spectrometer to detect adulterants in ground coffee with ~96.9% accuracy [2]. They explicitly noted that similar portable sensing could be applied to milk, juice, grain, and meat products to improve traceability and safety. In effect, MSI-enabled screening is becoming a valuable complement to conventional assays: it can rapidly flag suspect samples so that only those need further confirmatory testing. By facilitating frequent checks at multiple points in the supply chain, such methods are expected to bolster overall food quality control.

Multispectral Imaging (MSI) has gained attention in recent years as an innovative solution to this challenge [3]. By obtaining images of a food sample at a handful of discrete wavelengths, this technique can detect subtle changes in color and chemical composition associated with adulterants. Unlike simple visual inspection, MSI extends human vision into ultraviolet, infrared, and other spectral regions to reveal signatures that adulterants leave behind [4]. Just as crucially, it yields a spatial map of the sample, revealing not only whether adulteration is detectable, but also where in the product adulterants are distributed. The quickness, amount of information and non-consumptive testing indicates that MSI can potentially add a powerful new weapon in quality control of emerald. In the rest of the review, this work described the fundamental bases of this analytical approach as well as how it has been used to detect the adulteration of different classes of foods, from liquids to powders and meats. This paper also points out the advantages and limitations of the method.

Together, these features mean MSI can often catch problems that single-point sensors miss. For example, impurities clustered in one area of a powdered spice or meat slice can be visualized as distinct patches in a multispectral image. This spatial detail, combined with spectral “fingerprints”, allows algorithms to detect even low-level adulteration by pattern recognition. As new studies show, equipping MSI with chemometric or deep learning models greatly enhances its power. In fact, some researchers now advocate integrating MSI into routine production lines or regulatory checkpoints, since it can process many samples quickly and non-destructively.

2 Principles of MSI for adulteration detection

MSI is an evolved version of digital imaging and spectroscopy-based system which recognizes variation in food samples [5]. MSI involves the acquisition of a number of images of a sample at different wavelengths or bands in the electromagnetic spectrum, beyond the typical visible region. Comparing how a sample absorbs or reflects light at these chosen wavelengths tells us about its chemical composition and allows us to pick out anomalies. For example, a contaminated product might absorb more strongly at a wavelength associated with a particular dye or chemical, whereas a pure product would not. These spectral "fingerprints" can reveal even subtle adulteration.

In practice, a key advance has been the strategic selection of bands. Instead of capturing hundreds of contiguous wavelengths (as in hyperspectral imaging), modern MSI often uses only a few optimally chosen wavelengths. For instance, Yang et al. (2025) integrated a wavelength-selection algorithm into the sensor design and built a four-channel camera specifically for wine testing [6]. Using that four-band MSI device, they detected diluted or blended wine with about 97.5% accuracy. This example shows that even a simple MSI rig—when its filters target the most informative spectral bands—can perform remarkably well for a given task. By contrast, traditional single-band cameras would completely miss such chemical cues.

Another recent development is the use of advanced pattern recognition on multispectral data. Deep learning, in particular, has been applied to MSI cubes with great success [7]. For example, Xun et al. (2024) collected MSI cubes of 20 fish species and trained various classifiers on the spectral images [8]. A convolutional neural network (CNN) model achieved over 99% accuracy in identifying the species from MSI data, far surpassing older methods. Even simpler discriminant models (QDA, LDA) reached similar accuracy once features were extracted. Importantly, this study found that just 11 carefully selected bands (out of the full set) still yielded 98% accuracy, illustrating how AI can extract the essential differences from MSI data. These results suggest that by coupling MSI with intelligent algorithms, one can effectively recover detailed composition information that rivals what hyperspectral systems provide.

Unlike hyperspectral imaging, which collects tens or hundreds of continuous bands and generates large data volumes, multispectral systems focus on a limited number of informative bands (often 3–15 wavelengths). This reduces hardware complexity and speeds up data processing, allowing for more compact, field-ready devices. In practice, the wavelengths are chosen based on known optical markers of the product and potential adulterants (for example, targeting water absorption bands, fat absorption bands, or distinct pigment peaks) to maximize detection sensitivity with as few channels as possible.

A typical MSI setup for food analysis might use an array of LEDs or optical filters to illuminate the sample sequentially with specific wavelengths, spanning visible and near-infrared (NIR) regions known to reveal food composition. The resulting images are then processed by software. Techniques such as taking ratios between different bands, principal component analysis (PCA), or machine learning classification can highlight regions where the optical properties deviate from what is expected in an unadulterated product. An important advantage of imaging over single-point spectroscopy is the ability to visualize heterogeneity: MSI can produce a false-color image indicating where an adulterant is located within a sample (for instance, pockets of foreign material in a ground spice or clusters of an additive on a grain) [9]. Because MSI is non-contact and non-destructive, the same sample can be tested by other methods if needed, and testing can be done inline (in a processing facility) without halting production. These characteristics make MSI especially suited for rapid screening of foods for authenticity and purity.

3 Detection in dairy and liquid products

Dairy and other liquid foods are among the most frequently adulterated products, and they benefit greatly from MSI's sensitivity to compositional changes. Milk, for example, is often diluted with water or adulterated with substances like reconstituted milk powder, urea, or even dangerous chemicals (as seen in the melamine scandal). In the near-infrared (NIR) range, MSI can exploit the distinct absorption features of milk's components [10]. Because water has strong absorption at specific NIR wavelengths, watered-down milk produces a different spectral response than pure milk. Researchers have demonstrated that even a small amount of added water or other adulterants in milk can be detected by analyzing intensity changes at key wavelengths related to protein and lactose bonds versus water. In powdered milk, NIR MSI has successfully identified melamine crystals or other foreign particles by their spectral signatures, effectively mapping out tiny adulterant clusters within the powder.

Edible oils are another category where authenticity is critical and often compromised. Premium oils like extra virgin olive oil have historically been diluted with cheaper plant oils (e.g., soybean or sunflower), which are hard to distinguish by eye. Using MSI, inspectors can capture images in both visible and NIR bands to detect differences in oil composition. For instance, genuine olive oil contains natural pigments (such as chlorophyll and carotenoids) that absorb visible light differently than most seed oils. An MSI system tuned to pigment-sensitive wavelengths can flag samples that lack the expected olive-oil spectral profile [11]. In the NIR, differences in fatty acid composition between oils yield distinct spectral profiles that can be used by chemometric models to detect adulteration. Another kind of high-value liquid that is often diluted with far-less expensive sugar syrups, also has specific changes to its infrared spectra when syrups are used to dilute it. Such differences can be detected in a multi-spectral scan and thus can be used for identifying genuine honey from the artificial also by changes in the sugar content. In honey, the characteristic sugar profile (fructose vs glucose) and its deep color yield unique multispectral markers, allowing pure honey to be distinguished from sugar-syrup–adulterated samples by their differing spectral maps. In all these cases, MSI's sensitivity to water, pigment, and carbohydrate absorption can quickly flag inconsistencies that warrant lab follow-up. For example, Yeliz and Mahmut[12] developed an inexpensive multispectral sensing system (using a six-band AS7265x sensor) combined with a neural network to detect starch adulteration in raw milk. They collected MSI data from milk samples with varying starch levels and trained an ANN to classify them. Remarkably, their model achieved 100% accuracy in distinguishing adulterated from pure milk. This demonstrates that a compact MSI device, when paired with machine learning, can reliably identify even small starch additions. Such portable systems could enable farmers or processors to scan bulk milk on-site, providing rapid screening that supplements traditional lab tests.

4 Detection in cereal grains and flours

Grains and flours are susceptible to similar adulteration with extraneous or inferior material. Being processed in high mass these items can be visually overlooked and contain these small percentages of alien matter. MSI is able to increase grain quality inspection of people by featuring products that show different profiles with respect to the spectral signature [13]. For example, a batch of premium rice (such as basmati) mixed with a cheaper variety may not be obvious to the eye, but an MSI system can detect slight differences in kernel color and translucency at certain wavelengths, revealing off-type grains. Similarly, flour that has been extended with undeclared fillers—like chalk powder or cheaper flour from another source—will show spectral anomalies. By scanning flour samples, multispectral devices can pick up differences in reflectance (for instance, if talc or other minerals are present, they may reflect more strongly in specific bands than pure wheat flour). Likewise, mixing one grain's flour into another (for example, adding corn flour into wheat flour) leaves a distinct spectral signature, since each crop has unique constituents that absorb light differently in certain bands.

In bulk grains, optical screening with MSI can spot foreign matter (stones, husks, pests) by shape and color [14]. More subtly, small amounts of inferior grains or flours mixed in are a concern. For instance, a sack of wheat flour may sometimes contain traces of corn or barley flour. MSI can detect such contamination if the colors or spectral signatures differ. For example, Liu, Zhang[15] used MSI on maize kernels with 19 selected wavelengths and discriminated high-quality versus defective grains with 83 – 100% accuracy. This suggests that variations in protein or moisture content (reflected in NIR bands) can be learned by models. By extension, a similar multi-band MSI approach could reveal small percentages of substituted grain in bulk wheat or rice. Non-destructive MSI scanning of conveyor belts or stored bins could thus act as an automated sentinel, verifying that grain shipments meet label quality and contain no unauthorized dilutions.

Another common issue in grain products is the accidental or intentional inclusion of foreign botanical material (seeds, husks) or inorganic debris. Under MSI, these contaminants stand out: seeds from a different plant have distinct pigment and moisture content, leading to different responses in both visible and NIR bands. In practice, an automated inspection system can use MSI data to pinpoint and remove discolored or odd-looking kernels and particles that do not match the signature of the main product. This improves the purity of flour and grain shipments and can act as an anti-adulteration measure when, for instance, unscrupulous suppliers add non-food fillers to increase weight. Overall, MSI enhances our ability to ensure that cereal-based products remain true to their label and free from hidden additives.

5 Detection in herbs, spices, and plant powders

Dry, powdered products such as ground herbs and spices, tea, coffee, and cocoa are frequently targeted for adulteration because foreign matter can be blended in inconspicuously [16]. Here, MSI is especially valuable, since slight color and spectral changes can betray the presence of adulterants in an otherwise uniform-looking powder. Take turmeric powder as an example: it has been adulterated with cheaper starch-based fillers dyed yellow to mimic turmeric's color. A multispectral approach using a discrete set of visible and NIR wavelengths can detect this. In one study, researchers used about 8 – 10 wavelengths spanning from the blue visible region into the near-infrared to successfully identify turmeric mixed with yellow-dyed flour; the system captured differences in spectral reflectance that correlated with the percentage of adulterant, even when the coloration looked similar to the eye. By applying chemometric analysis (such as principal component analysis) to the multispectral data, they could quantify the level of adulteration with high sensitivity.

Spices like chili powder and paprika have similarly been examined with MSI to catch illegal dyes or fillers like brick dust [17]. These adulterants often introduce unique absorption features in the visible range (unexpected reds or yellows) that multispectral cameras readily detect. Authentic saffron—one of the world's most expensive spices—has a distinct spectral signature due to its carotenoid content, whereas fake saffron strands (made from dyed corn silk or other plant fibers) show different color responses that can be flagged by the right set of spectral filters. Likewise, tea leaves mixed with dyed or foreign leaves can be identified in the NIR [18], because genuine tea and adulterant leaves differ in moisture and organic compound profiles, affecting their reflectance. Ground coffee is another example: low-grade coffee or chicory mixed into pure coffee can be revealed by an MSI scan in visible and IR bands, which picks up subtle color and texture differences or dissimilarities in chemical composition. Cocoa powder, another valuable commodity, can also be authenticated through MSI—pure cocoa shows characteristic NIR absorption due to cocoa butter and polyphenols, whereas samples adulterated with fillers like carob or starch exhibit altered spectral patterns. Even a common seasoning like ground black pepper can be tested: researchers have found adulteration with papaya seeds, which look similar but are chemically different. Under multispectral analysis, subtle differences in color and texture between genuine pepper and counterfeit seeds were detected, flagging this form of fraud. In addition, Alighaleh, Pakdel[19] used visible/NIR MSI with machine learning to classify genuine versus adulterated saffron (a very expensive spice) and achieved 99.52% accuracy. No chemical test was needed – the classifier simply learned the spectral patterns of the filaments.

6 Detection in meat and seafood products

Meats and seafood are prime targets for fraud (species substitution, water injection, etc.). MSI can help authenticate these products too. For instance, normal meat color arises from myoglobin, fat, and water content; diluting or adding extenders (soy, starch) alters the reflectance at hemoglobin-related bands. MSI cameras tuned to the near-IR water band (around 970 nm) can map moisture distributions, so water-injected meats become obvious. Already, imaging systems have been shown to distinguish cuts of beef vs pork vs poultry by trained spectral models.

Meat and seafood adulteration often involves substituting one species for another or mixing lower-quality meat into higher-value products [20]. These frauds can be very difficult to spot by eye once the product is processed or ground, but MSI offers a solution by detecting subtle differences in tissue composition. Muscle from different animal species varies in attributes like myoglobin content, fat distribution, and texture—all factors that influence how light is absorbed and reflected. By selecting appropriate wavelengths in the visible and NIR spectrum, an MSI system can highlight these differences and thus discriminate between meats [21].

One notable incident was the European horsemeat scandal, where horse meat was found in products labeled as beef. Studies have since shown that horse meat and beef exhibit distinct spectral profiles. Using multispectral (or hyperspectral) analysis, researchers are able to classify which pixels in an image of a meat sample correspond to beef and which to horse, especially under controlled lighting [22]. In more routine scenarios, investigators have detected pork or poultry blended into ground beef. For example, an imaging study on minced meat used wavelengths from about 400 to 1000 nm and achieved high accuracy in identifying pixels of chicken mixed within beef mince. The level of adulteration could even be quantified: as more chicken was added, certain wavelength bands (related to poultry's higher oxidation of myoglobin or different fat signatures) showed systematic changes. Such imaging-based models enable rapid screening without needing to send samples for DNA analysis [23]. Similarly, if a processed meat product contains non-meat fillers (such as added soy protein or starchy extenders), MSI can detect them because those plant-based additives have spectral features—particularly in the NIR—that differ from pure muscle tissue.

Seafood authenticity can also benefit from multispectral techniques. Fillets of different fish species can look alike once cut and packaged, but their flesh has different optical characteristics due to variations in muscle structure and water/fat content. MSI in the visible/NIR range can differentiate fish species by these features [24]. For instance, a camera tuned to a handful of wavelengths was able to distinguish between cod and haddock fillets by capturing differences in their reflectance patterns. Signs of fish quality degradation (such as old fish sold as fresh, or previously frozen fish passed off as never frozen) can also be detected through specific spectral indicators (for example, changes in surface color or water absorption bands). For example, fish that has been frozen and thawed often exhibits subtle shifts in surface texture and moisture distribution; an MSI system focused on water-sensitive wavelengths can capture these cues, helping flag "fresh" fillets that were actually frozen earlier. By deploying MSI as a screening tool, meat and fish processors can verify species and detect low-quality or substitute ingredients on the spot, thereby protecting consumers and honest producers against fraud.

7 Detection in beverages and other products

Beverages such as fruit juices and wines are also vulnerable to adulteration, and MSI can help verify their authenticity. Fruit juices may be diluted with water or blended with cheaper juices, and artificial colors or sweeteners can be added to mask these changes. These adulterations alter the optical properties of the juice. Using MSI in the visible range, inspectors can detect anomalies in color that correspond to unauthorized additives. For example, an unusually uniform redness might indicate a synthetic dye in what is supposed to be pure cherry juice. Likewise, NIR bands can reveal differences in sugar or organic acid content when a premium juice (like pomegranate or orange) has been cut with sugar syrup or a less expensive juice (like apple). Researchers have shown that the spectral profiles of pure versus adulterated juices differ enough that multivariate analysis can classify them correctly. As a case in point, a study found that pure pomegranate juice could be distinguished from samples extended with grape or pear juice by picking up subtle shifts in specific wavelength absorbances linked to pomegranate ' s unique pigments.

Wine fraud is another concern: low-quality wine or even other alcoholic beverages are sometimes passed off as vintage varietals. MSI offers a rapid screening method to complement chemical tests [25]. Genuine wines have characteristic absorption features in the visible spectrum (due to phenolic compounds) that change if the wine is watered down or mixed with a different grape source. These multiple wavelength MSI spectra of color can be used to raise red flags over irregularities: for example, a questionable dilution may be suspected if the correct absorption intensity at a tannin related wavelength is lower than expected for the indicated variety and age. While the provenance of expensive wine is still often determined by lab work and the judgment of an expert taster, a prescreen based on imaging could help pinpoint which bottles require more rigorous analysis. More generally, any liquid or homogeneous foodstuff may be screened regarding its consistency using MSI, so that this is a highly versatile tool for ensuring food authenticity.

8 Future research directions

The MSI has some challenges to overcome for it to be widely used in the food quality control sector. One significant concern pertains to uniform calibration and accuracy characteristics among various lots, locations, and devices. There is also natural variation in food—due to growing conditions, seasonal differences, subtle differences in processing—which can mean that detection models need to be robust if a false alarm is not to be declared. It is crucial to have big representative spectral library of genuine and adulterated samples to be used for training robust models. Practical barriers come into play as well, with high-performance multispectral cameras and filters being costly, potentially limiting the use to large manufacturers, smaller producers, or regulators. Additionally, many instruments need both controlled lighting and climate conditions to maintain their results.

To address these issues, several strategies are being pursued. Researchers are developing global calibration models and transfer-learning methods to align data from different sensors. There is also work on open-access spectral databases of foods, so that new devices can leverage collective knowledge of authentic signatures. In practice, some systems now incorporate built-in reference panels or automatic white-balancing to reduce variability. Furthermore, the cost of MSI hardware is steadily dropping: new research-grade sensors are derived from smartphone camera components, and educational kits are teaching non-experts how to build spectrometers. These efforts help mitigate the earlier limitations on device consistency and expense.

Recent developments, however, are mitigating these shortcomings. Low-cost sensors and even spectrometers based on smartphones are attracting interest as potential tools for cheap, on-site testing for small-scale producers. Improvements in data analysis are also strengthening MSI: integrating it with machine learning and AI, for example, enhances detection accuracy and let models learn intricate patterns of adulteration. And on the software side, user-friendly interfaces and cloud-based platforms are beginning to make the analysis of spectral data accessible to people outside the field.

Concurrently, MSI is moving toward integration with other technologies. For instance, automated conveyor imaging systems can combine MSI with computer vision to flag suspicious containers or packages in real time. Some research envisions linking MSI outputs to digital supply-chain databases or blockchain ledgers, enabling traceable records of authenticity checks. Moreover, handheld MSI devices with wireless connectivity could allow regulatory agencies to scan foods in markets or ports instantly, uploading the spectral fingerprint for remote validation. Such interconnected solutions point to a future where spectral screening is embedded throughout food production and distribution.

Looking further ahead, several exciting opportunities could expand the impact of MSI in food safety. For example, integrating MSI with automation and robotics could enable real-time removal of adulterants on production lines: imagine robotic arms pulling out contaminated grains flagged by an imaging system. Advances in deep learning may allow future models to detect more subtle or novel forms of adulteration without manual feature selection. There is also growing interest in networked spectral databases (possibly shared across industry and academia) that would allow new devices to access extensive libraries of food signatures, further improving accuracy. Moreover, handheld MSI devices combined with smartphone connectivity could empower regulators and even consumers to perform rapid checks in the field.

9 Conclusion remarks

MSI has demonstrated itself as a versatile and effective approach for the rapid detection of food adulteration across a wide range of products. Its combination of spectral and spatial information provides a distinct advantage in uncovering adulterants that elude ordinary visual inspection or single-point chemical tests. By using a small number of well-chosen wavelengths, MSI systems can non-destructively spot everything from watered-down milk to counterfeit spices and mislabeled meats, allowing many more samples to be screened quickly before confirmatory lab tests. With ongoing technological advances and proper integration into quality control workflows, MSI holds great potential to significantly enhance food authenticity and safety assurance in the future. Despite its strengths, MSI still faces challenges in terms of device calibration, cost, and environmental sensitivity. Nevertheless, recent technological trends—such as the development of low-cost sensors, user-friendly analytical platforms, and model-transfer techniques—are progressively lowering the barriers to widespread adoption. Moreover, MSI is increasingly being integrated with automation, wireless connectivity, and supply chain systems, enhancing its value within modern food safety frameworks.

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