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Review

A Comprehensive Review: Hyperspectral and Modern Spectroscopy Identification of Yogurt Adulteration

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Abstract

Yogurt is a valued dairy product known for its taste and texture, but these qualities also make it prone to adulteration. Common practices include adding starch, milk powders, vegetable oils, sweeteners, preservatives, and, in some cases, even harmful heavy metals, which can reduce quality and harm consumer health. Conventional analysis can be selective but is often destructive, labor-intensive, and slow for routine screening. The rapid, non-destructive alternatives provided by modern image-based spectroscopy can probe both composition and spatial heterogeneity in yogurt. This review summarizes the developments of hyperspectral imaging (HSI) and new spectroscopic methods of detecting yogurt adulterants, including Near-Infrared (NIR), Terahertz spectroscopy, Raman, Laser-Induced Breakdown Spectroscopy (LIBS), Nuclear Magnetic Resonance (NMR), vibrational mid-IR/FTIR, and UV-V are prominent methods. Spectroscopy gives robust chemical fingerprints (NIR/Raman/FTIR), and HSI gives space (LIBS/THz), as well as elemental and bulk properties; the combination of the two with ML enhances the precision and generalization. Key challenges include product variability, fermentation effects, calibration transfer, and the lack of publicly available datasets. To address these, future priorities should focus on developing portable instruments, applying multimodal data fusion and transfer learning, ensuring interpretable AI models, and establishing standardized protocols for routine, non-destructive yogurt authenticity testing.

Keywords: Yogurt; Adulteration Identification; Hyperspectral Imaging; Spectroscopy Techniques

1. Introduction

Yogurt is made by fermenting milk with two live bacterial cultures, Lactobacillus bulgaricus and Streptococcus thermophilus, which convert lactose into lactic acid. The bacteria thicken the milk and give it a tangy flavour by fermenting the lactose in the milk to produce lactic acid. Other substances produced during fermentation, including acetaldehyde, diacetyl, and acetoin, help to give yogurt its flavour and aroma [1]. Due to its nutritional qualities, yogurt is a widely consumed food product regarded as a healthy food. In addition to serving as a rich source of probiotics that support gut health, yogurt also provides high-quality protein, calcium, and essential micronutrients. Yogurt comes in various flavours and can be eaten on its own or combined with other foods to make sauces, dips, and desserts. Yogurt is prepared using milk from cows, goats, or sheep and can be produced with different fat contents, from non-fat to full-fat. There are also different styles of

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yogurt, such as Greek yogurt, which is strained to remove some of the liquid buttermilk, resulting in a thicker and creamier product [2]. Yogurt can also be produced with added fruit, sweeteners, or flavourings, but it is important to be aware of the sugar content of flavoured yogurts, as some brands can contain high levels of added sugars. However, the increasing incidence of food adulteration has raised concerns about the quality and safety of yogurt. Adulteration of yogurt can occur by adding water, diluted or synthetic milk, or other substances, which can affect the product's nutritional value and sensory properties and pose serious health risks to consumers. An illustration of the compositional differences between pure and adulterated yogurt is shown in Figure 1.

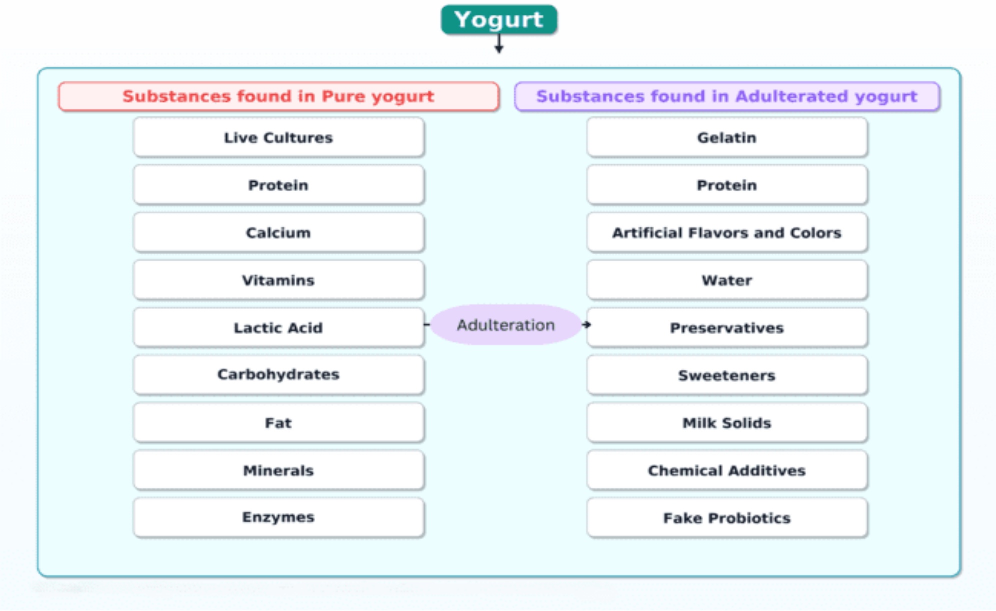


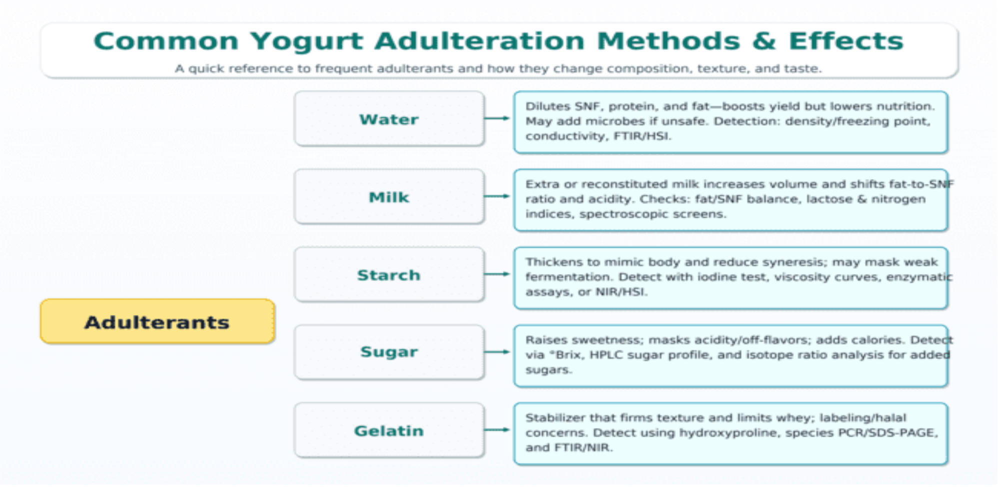
Figure 1. Comparison of substances present in pure and adulterated yogurt.

Although several studies have employed sensory evaluation to detect adulteration in dairy products, there remains a need for reliable and precise techniques to identify adulteration in yogurt. Sensory analysis, also known as sensory evaluation, refers to a collection of methods used to accurately interpret human sensory responses to food while avoiding biasing effects [3]. Various analytical techniques, including chemical and physical methods, have been developed to detect yogurt adulteration. Hyperspectral imaging has proven to be an effective technique for detecting yogurt adulteration; however, alternative methods can also be applied for this purpose. Figure 2 illustrates different spectroscopic instruments that are typically used to detect adulteration.

Figure 2. Different types of spectroscopic devices used for the identification of adulterants.

Chromatography is one of such alternative methods where various components in a sample are separated on the basis of their chemical characteristics. The presence of adulterants in yogurt can be determined through chromatography, which involves separating the components of the sample in order to establish the presence of any compounds that are not a part of the sample. To enhance the sensitivity and selectivity of the technique, chromatography may be coupled with other methods of analysis, including mass spectrometry or infrared spectroscopy [4]. The other alternative is the DNA-based authentication method, whereby genetic markers belonging to the yogurt are identified, which can be used to validate the origin and authenticity of the yogurt. There is a wide variety of foods that are adulterated [5]. The technique is based on the ability to identify certain DNA chains that are specific to the bacteria that make the yogurt. It may be employed to differentiate any bacterial strains and identify any contaminants or adulterants. The third alternative approach is isotopic analysis, which is the measurement of the isotopic composition of the elements in the yogurt. The graphical origin of the yogurt can be established through the isotopic composition of elements like carbon, nitrogen, and oxygen, and any variation in the composition can be used to determine whether it has been adulterated or contaminated. Both alternative methods have their own merits and demerits, and the decision to use one or the other method will be determined by the requirements of the yogurt industry and the type of adulterants that might be used. Nevertheless, HSI is an effective and promising method of yogurt adulteration detection. It may be merged with other procedures to study yogurt authenticity and safety in a general way [6]. However, some adulterants have serious health effects, sometimes in the long term. Consumption of melamine at levels above the safe limit can cause kidney failure and death in children [7]. Methods used to identify counterfeit dairy products are time-consuming and require a sample preparation step. This calls for different types of chemical reagents [8], requires extensive sample preparation, and may only be able to detect some types of adulterants. HSI is an emerging technology to detect food adulteration, such as the yogurt. HSI is a method of photographing an image of a sample with a spectrometer and an imaging device to measure the spectrum of reflected or transmitted light at every point in the image. Chemical composition of the sample can be estimated using this information, and any changes or adulterants can be detected. This paper is a review of the existing state of the art in detecting adulteration of yogurt and proposes that HSI is a promising method. We have discussed the theory of HSI and its benefits compared to other methods of analysis [9]. We also give details on the HSI methods applied in detection of adulteration on yogurt, near-infrared (NIR), mid-infrared (MIR), and Raman spectroscopy. Finally, the prospects of hyperspectral imaging (HSI) are discussed as a quality control instrument in the yogurt sector and the role it can play in maintaining the safety and authenticity of yogurt products. Hyperspectral reflectance imaging has been used in many HSI-based studies of food and agricultural materials, and records the light reflection in the visible spectrum up to the shortwave infrared spectrum. Fluorescence is the emission of light of a longer wavelength in response to short-wavelength light incident on a material, which can be used to understand the structure of the material under test. Just like reflectance, fluorescence also can be measured via spectroscopy or by HSI [10].

2. Adulteration of different substances in yogurt



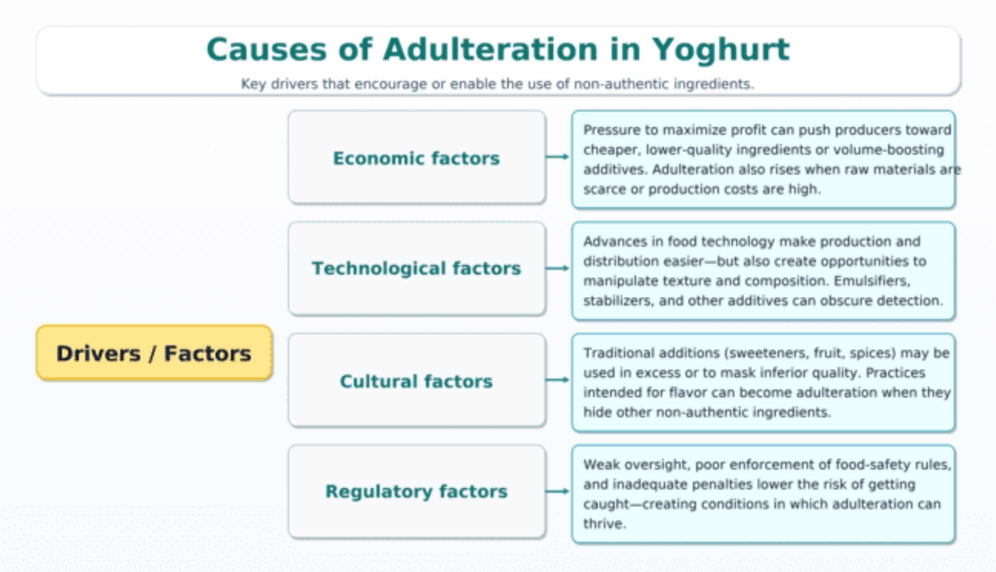
Water	Dilutes SNF, protein, and fat—boosts yield but lowers nutrition. May add microbes if unsafe. Detection: density/freezing point, conductivity, FTIR/HSI.
Milk	Extra or reconstituted milk increases volume and shifts fat-to-SNF ratio and acidity. Checks: fat/SNF balance, lactose & nitrogen indices, spectroscopic screens.
Starch	Thickens to mimic body and reduce syneresis; may mask weak fermentation. Detect with iodine test, viscosity curves, enzymatic assays, or NIR/HSI.
Sugar	Raises sweetness; masks acidity/off-flavors; adds calories. Detect via °Brix, HPLC sugar profile, and isotope ratio analysis for added sugars.
Gelatin	Stabilizer that firms texture and limits whey; labeling/halal concerns. Detect using hydroxyproline, species PCR/SDS-PAGE, and FTIR/NIR.

Figure 3. Common adulterants in yogurt and their functional roles.

Several substances are commonly used to adulterate yogurt, as illustrated in Figure 3, along with their functional roles. It is important to note that adding any of these substances to yogurt can alter the product's nutritional content and sensory properties and pose health risks to consumers. Therefore, dependable techniques are essential for identifying and preventing yogurt adulteration.

3. Cause of adulteration in yogurt

The reasons for yogurt adulteration are not the same everywhere. They often depend on economic, technological, and even cultural influences, as shown in Figure 4.



Pressure to maximize profit can push producers toward cheaper, lower-quality ingredients or volume-boosting additives. Adulteration also rises when raw materials are scarce or production costs are high.

Advances in food technology make production and distribution easier—but also create opportunities to manipulate texture and composition. Emulsifiers, stabilizers, and other additives can obscure detection.

Traditional additions (sweeteners, fruit, spices) may be used in excess or to mask inferior quality. Practices intended for flavor can become adulteration when they hide other non-authentic ingredients.

Weak oversight, poor enforcement of food-safety rules, and inadequate penalties lower the risk of getting caught—creating conditions in which adulteration can thrive.

Figure 4. Economic, technological, and cultural factors contributing to yogurt adulteration.

The drivers of adulteration are often connected and not always easy to separate. Tackling the issue requires joint efforts from producers, regulators, and consumers. Stronger food safety rules, better public awareness, and the use of modern testing technologies can all help reduce adulteration and ensure people get safe and good-quality yogurt.

4. Detection techniques for yogurt adulteration and the superiority of HSI

In this study, the techniques used for yogurt adulteration detection include Terahertz spectroscopy, Laser-Induced Breakdown Spectroscopy (LIBS), Nuclear Magnetic Resonance (NMR), Raman spectroscopy, Near-Infrared (NIR) spectroscopy, Vibrational spectroscopy, UV-Vis spectroscopy, and Hyperspectral Imaging (HSI). Table 1 outlines their principles, uses, results, and the strengths and weaknesses of each method. Additionally, the introduction discusses complementary non-spectroscopic approaches such as chromatography, DNA-based authentication, and isotopic analysis that can be used to support confirmation workflows where appropriate. This study highlights how HSI outperforms traditional and modern spectroscopic techniques. The comparative ranking of these methods is presented in Figure 5. HSI simultaneously captures spatial and spectral information for every pixel as shown in Figure 13, enabling non-destructive, reagent-free mapping of localized or multi-component adulterants with minimal sample preparation and straightforward chemometric modelling. This pixel-resolved "data cube" concept underpins HSI suitability for rapid screening and inline quality control.

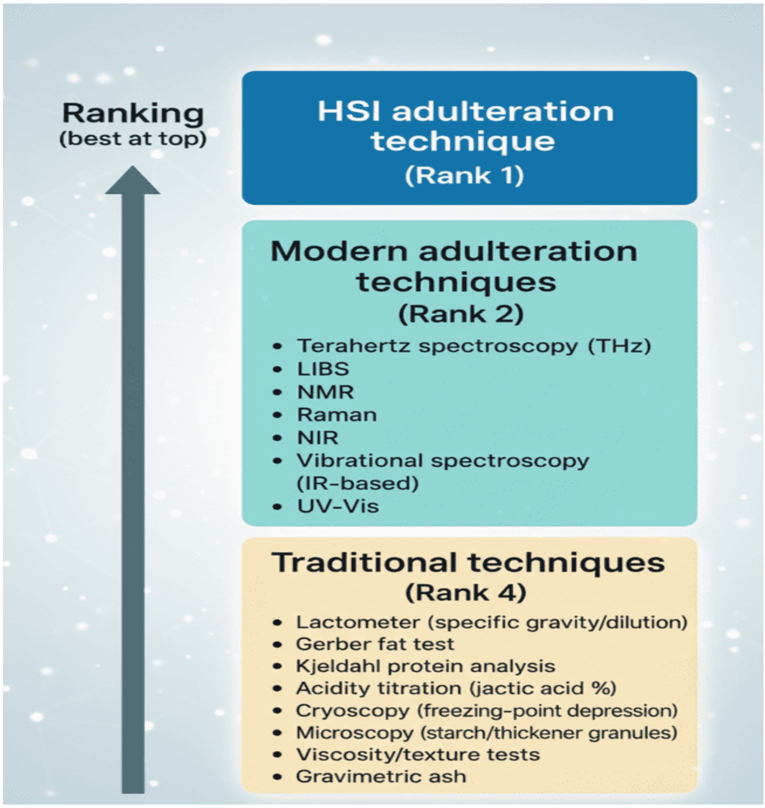


Figure 5. Ranking of yogurt adulteration detection methods, showing HSI at the top.

5. Different techniques for adulteration detection in yogurt

Spectroscopic techniques work within specific frequency ranges, which depend on the process under study and the magnitude of the energy change involved [11]. Table 1(a) summarizes Principles & Phenomena of various spectroscopic techniques and Table 1(b) outlines their applications, advantages, and disadvantages. A visual overview of these techniques is also be seen in presented in Figure 6.

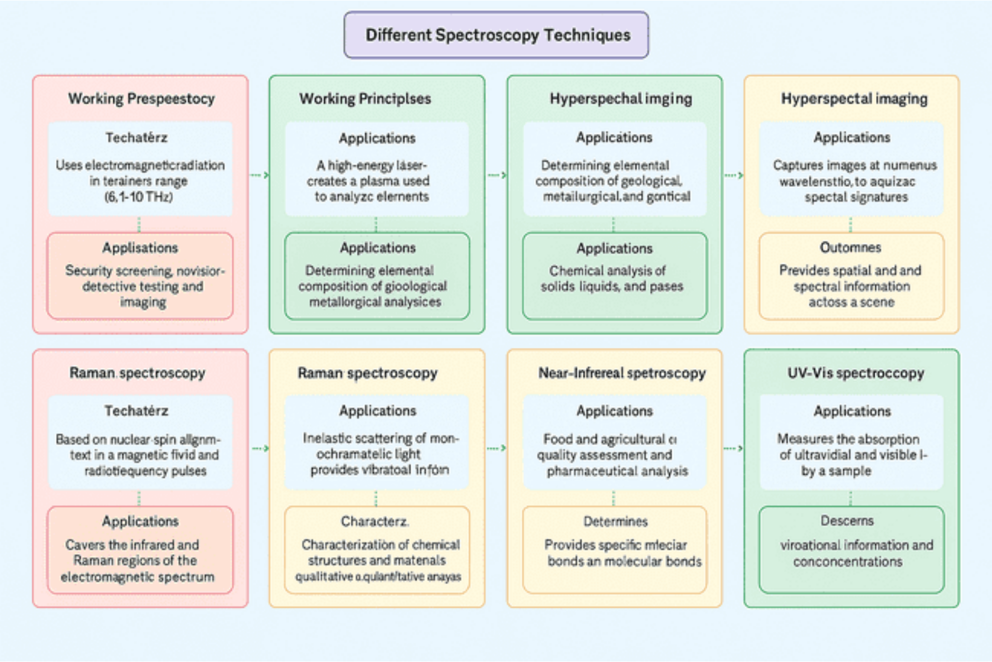


Figure 6. Overview of spectroscopic techniques: principles, outcomes, and applications.

Table 1 (a) Spectroscopic Techniques, Principles & Phenomena.

Spectroscopy Techniques	Working principle	Phenomenon	Outcomes	Ref
Terahertz Spectroscopy	Using reflected magnetic fields at hundreds of gigahertz → terahertz frequencies	Molecular vibration shifts	Delivers qualitative and quantitative information about food materials.	[12]
Laser-Induced Spectroscopy	A focused laser pulse produces plasma of excited atoms returning to the ground state.	Atomic or optical emission	Useful for both identifying and characterizing food components.	[13]
Hyperspectral imaging (HSI)	Spectral image acquisition in stitching Discrete and narrow wavebands in the spatial direction	Absorption, transmission, or detection of features closely related to quality	Identify individual traits or characteristics directly linked to quality.	[14]
NMR	Absorption tendency and the emission energy in radio frequency.	The count of resonant nuclei is determined as the signals are applied directly.	Detects various categories of chemical compounds concurrently.	[15]
Raman spectroscopy	Evaluates the transfer of photon energy from the sample's molecules using optical measurement.	Molecular vibrations generate the spectrum as bond stretching and bending result from polarizability variations.	Reveals the molecular framework of chemical substances. Detects functional groups in chemical molecules.	[16]
Near Infrared spectroscopy	Evaluates how the sample absorbs electromagnetic radiation across the 780–2500 nm spectrum.	Absorption at a given wavelength can shift based on the food's makeup, its origin, and its specific type or genetic traits.	Food items can be identified by their distinct spectra, which depend on particular wavelengths and diffraction.	[17]
Vibrational spectroscopy	Evaluates the incident light interacting with the sample to identify what is absorbed, scattered, transmitted, or reflected.	The interaction between electromagnetic radiation and the vibrational or excited states of atomic nuclei.	Identification and authentication through qualitative analysis to detect food composition and its properties	[18]
UV-Vis spectroscopy	Determines how much light is absorbed by the sample at particular wavelengths within the UV-Vis spectrum.	Beer's Law states that a solution's concentration is directly related to the quantity of light it absorbs.	The absorption spectrum serves as a fingerprint to identify compounds.	[19]

Table 1 (b). Spectroscopic Techniques, Applications & Performance.

Spectroscopic Technique	Application	Advantages	Disadvantages	Ref
Terahertz Spectroscopy	Detection of foreign matter (stones, nails, plastic, hair, etc.) in	Data bandwidth is higher than wireless protocols such as	It does not support long-distance communication due to scattering and absorption by clouds, dust,	[12]

	foodstuffs.	802.11b.	rain, etc.	
Laser-Induced Spectroscopy	Determining mixing - Determining the geographical origin	Laser-induced breakdown spectroscopy is an extremely useful research and analysis tool. LIBS analysis is very versatile because it can be used on any material.	There is significant shot-to-shot variation in intensity, mostly because the laser does not interact with the sample similarly for each laser pulse.	[13]
Hyperspectral imaging	Verify the original. Evaluate chemical and physical properties.	Acquiring spatial and spectral information simultaneously, chemical-free, non-destructive, minimal sample preparation	Challenges in online and offline implementation related to the control of external factors, such as the complex nature of data and its analysis, ambient light, and high cost	[14]
NMR	Uncover academic fraud - address the geographic source.	Rapid, chemical-free, non-destructive screening of complex matrices	Significant overlapping of marker signals can lead to false interpretations.	[15]
Raman spectroscopy	Detection of adulteration in milk and milk products, beverages. Honey and grains Recognizing species-based fraud within meat and fish commodities.	No sample preparation is required. They are not interfered with by water. Non destructive Extremely specific, resembling the unique chemical fingerprint of a substance.	It cannot be used for metals or alloys. The Raman effect is very weak. Sensitive as highly sophisticated instrumentation is required for detection.	[16]
Near Infrared spectroscopy	Analyzing freshness, storage life, authenticity, mislabeling risks, and both chemical and microbial characteristics of seafood.	Inexpensive, simple, non-destructive, chemical-free, sample preparation, accessible, portable, and requiring no hand-held equipment.	The presence of overtone and combination band superposition and signal	[17]
Vibrational spectroscopy	Structural studies, Verification of food items	It has advantages over widely used NMR spectroscopy techniques, such as short analysis time, low volume requirement, and the possibility of in situ analysis.	Atoms or monatomic ions have no infrared spectra, so they cannot be analyzed. Using infrared spectroscopy requires highly sensitive and properly tuned instruments.	[18]
UV-Vis spectroscopy	Identification of food compounds based on the absorption spectrum of their native Geographic.	The advantage of the UV-Vis spectrophotometer is its quick analysis capability and ease of use.	The major disadvantage of using a UV-Vis spectrometer is its time to prepare. Setup is critical when using a UV-Vis spectrometer.	[19]

5.1. Terahertz Spectroscopy THz

Terahertz spectroscopy THz is a powerful technique that uses electromagnetic radiation in the terahertz range (.1 to 10 THz) to study the properties of materials. THz spectroscopy has been widely studied in various fields, including security screening, astronomical research, communications, non-destructive testing, and dental caries imaging. Compared to X-rays, the THz technique is safer for operators and targets because the THz wave has lower photon energy, which does not cause phantomization and damage to biomolecules [20]. Terahertz radiation falls between the microwave and infrared regions of the electromagnetic spectrum, and it is characterized by its ability to penetrate many materials without causing damage [21]. Terahertz spectroscopy works by measuring the absorption and reflection of terahertz radiation by a sample. Initially, the use of spectroscopy in the THz range was limited because suitable sources and detectors were not yet available. At that stage, a THz gas laser served as the primary pulsed THz source, driven mainly by a CO_2 laser to excite the roto-vibrational states of gas molecules, producing a continuous-wave, single-frequency beam with watt-level power [22]. When terahertz radiation interacts with a material, it causes its molecules to vibrate and rotate. These vibrations and rotations produce unique spectral signatures that can be used to identify the material's composition, structure, and other properties [23].

The terahertz spectrum contains various frequencies corresponding to different molecular vibrations and rotations. As a result, terahertz spectroscopy can provide detailed information about a sample's molecular structure and composition. This information can be used to identify unknown materials, detect impurities or defects, and study materials' physical and chemical properties. There are numerous applications of terahertz spectroscopy in other areas, such as in materials science, chemistry, biology, and medicine. A summary of some of these applications is provided in Figure 7.

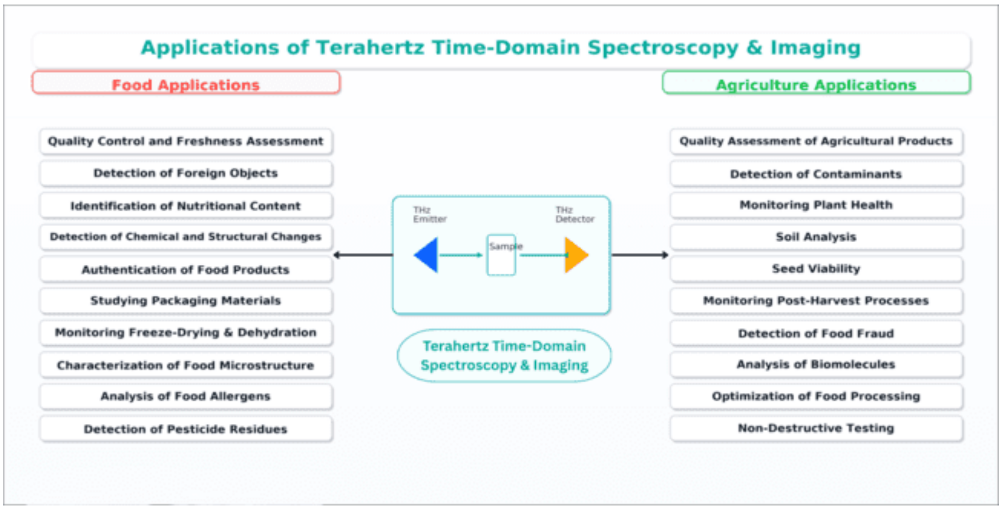


Figure 7. Applications of Terahertz Spectroscopy in Scientific, Technological, and Food.

It can be used to study an extremely wide variety of materials, including solids, liquids, and gases, and can be applied to study the properties of materials at the nanoscale. Terahertz spectroscopy is an effective analysis tool to give meaningful information regarding the physical and chemical characteristics of materials [24]. Its ability to penetrate many materials without causing damage makes it a useful tool for many applications. The Terahertz spectroscopy technique is being used to detect adulteration in various food products, including yogurt [25]. Yogurt is a fermented milk product that contains lactic acid bacteria, which provide a specific taste and texture to it. When the unscrupulous manufacturers put fillers or use low milk products, i.e., milk serum or skim milk, to dilute the yogurt and gain more profits, this can alter the yogurt. Another adulteration is the introduction of additives and preservatives to the yogurt. It is possible to detect adulteration of yogurt using terahertz spectroscopy after analysing the absorption spectra of the yogurt samples. Terahertz radiation can pass through the sample and be absorbed by the molecular vibrations of the components in the sample [26]. Using the absorption spectra of the yogurt samples, the distinct spectral characteristics of the components can be determined, and any variation of the anticipated spectra can be detected. Adulteration in yogurt by analysis of water content in the sample has been detected using terahertz spectroscopy. Pure yogurt samples usually contain less water as compared to adulterated samples of yogurt [27]. It is possible to detect changes in the water content and determine the presence of fillers or other additives. They analyzed the absorption spectrum of the water molecules in the sample [28]. In yogurt, terahertz spectroscopy has been applied to identify the adulteration procedure by the water content in the sample. This is because adulterated yogurt samples usually contain low water content as compared to pure yogurt samples.

5.2. Laser-Induced Breakdown Spectroscopy

In Laser-Induced Breakdown Spectroscopy (LIBS), a sample of small size is vaporized to produce plasma using a high-energy laser pulse. The technique has become popular due to its special features, broad applicability, little or no sample preparation methods, speed, low cost, and other scientific applications. LIBS can also be used remotely to detect standoff, and this has extended its applications [29]. This light is emitted by the plasma, and the elemental composition of the sample is determined. In LIBS, a small portion of the sample is vaporized by a focused laser pulse to form a plasma plume releasing light as it cools. The light that the plasma emits carries with it the elemental composition of the sample, since each element emits light at a characteristic set of wavelengths or frequencies. The identity and the amount of the elements in the sample can be identified by analyzing the spectrum of the emitted light[30].

There are a number of benefits to LIBS compared to other spectroscopies. It is a non-destructive method that does not need much sample processing, and therefore, it can be used in situ or in the field. It can also process different materials, such as liquids, gases, and solids. Also, LIBS is quite rapid, and the analysis time will be only a couple of seconds to a couple of minutes. LIBS can be used to study metals, geological, and biological tissues. In the metallurgical industry, LIBS has been used in the study of alloy composition, contaminants, and quality control of the metals used in manufacturing [31]. LIBS is used in geology to determine mineral composition, examine the composition of rocks and soil, and detect trace elements. Biological applications of LIBS include the study of tissue composition and also diagnosis of diseases. LIBS is an effective method of analysis, which is applied in all sectors. The capability to analyze samples on site, without necessarily doing a lot of sample preparation, makes it a valuable tool to use in many applications. In yogurt, we can determine the occurrence of adulteration through LIBS by examining the elements of the yogurt. The chemical components of some of the adulterants used, e.g., starch, sugar, and gelatin, are of a different composition than the elements initially present in yogurt. These adulterants can ultimately be observed by measuring the emission spectrum of the plasma that results associated with the laser pulse. In order to determine using LIBS whether a yogurt is adulterated, a sample of the yogurt is inserted in a sample holder, and one then focuses a laser on the sample. [32]. A laser pulse vaporizes the sample and excites a small portion of the sample into a plasma that emits light. Using a spectrometer, the analytical light is analyzed to determine the elemental composition of the sample. The plasma obtained can be compared to a reference spectrum of pure yogurt to test whether there are differences in the obtained spectra. If the sample spectra exhibit peaks that are absent in the reference spectra, this may indicate the presence of adulterants. The concentration of impurity can also be determined by observing the intensity of the peak of the emission [33]. Adulteration of yogurt can be identified by LIBS through interpreting the elemental composition of the yogurt sample. This is a non-destructive method, thus speedy and accurate, hence a significant help in controlling the quality of food, as demonstrated in Figure 8.

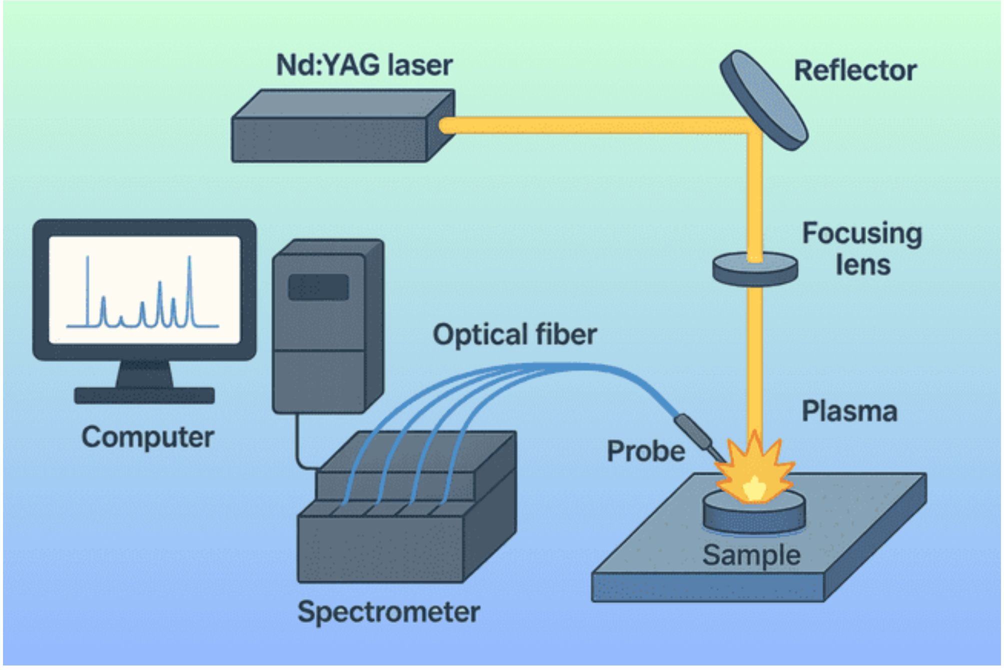


Figure 8. Basic view of LIBS for identification of adulterants using [34].

In the case of the yogurt, LIBS can identify the adulteration through an examination of the elemental composition of the sample. To illustrate, fillers or other additives can consist of things not usually in yogurt [35]. The spectral data can be analyzed to determine whether the elemental composition is deviated or not, and it is also possible to identify the non-yogurt components.

5.3. Nuclear Magnetic Resonance (NMR)

Nuclear Magnetic Resonance (NMR) is an analytical technique that is currently being used a lot in researching physical, chemical, and biological properties of materials. It functions based on electromagnetic radiation absorption between the wavelengths of 750nm to 2500nm and works on molecules with C-H, N-H, S-H, and O-H bonds [36]. The technique relies on the interaction between atomic nuclei and external magnetic fields. Placed in a magnetic field of sufficient strength, the nuclei of some atoms, including hydrogen, may be excited by a radiofrequency (RF) pulse and then release some of it at one or more characteristic signals. In NMR, the sample is put into a strong magnetic field, usually between 0.5 and 20 Tesla. A series of RF pulses is then directed to the sample, where the nuclei in the sample absorb and emit energy at characteristic frequencies [37]. These are read in a coil, and the data that is generated is analyzed to produce a spectrum of the chemical and physical properties of the sample. One key benefit of NMR is that there is no need to degrade or perform surgical interventions on a sample, and the sample can be revisited or used in other studies.

Detailed data on the structure, dynamics, and interactions of molecules in solution or solid state can also be obtained using NMR. NMR has very wide applications in several aspects, which include: chemistry, physics, biology, and medicine [38].NMR is used in chemistry to determine the chemical structure and composition of compounds, chemical reaction mechanisms, and impurities or contaminants in a sample. In biology and medicine, NMR has become an important tool to study the structure and dynamics of proteins, nucleic acids, and other biomolecules, as well as being used extensively as a non-invasive tissue-level imaging technique in living organisms. NMR is an effective and flexible analytical method that is used in a broad spectrum of domains. The fact that it can provide detailed information about the physical and chemical characteristics of samples gives it a role to play in research, quality control, and process optimisation in most industries [39]. Analytical NMR spectroscopy comes with great power, which detects food adulteration even in yogurt. Adulterants in yogurt may be in the form of water, solids of milk, or other substances that may compromise the quality of the yogurt and may be hazardous to the consumer. The principle of NMR spectroscopy is to subject the sample to a powerful magnetic field and test how the atomic nuclei react to the electromagnetic field. In every nucleus, the frequency response will have a specific characteristic that one can use to determine its chemical structure and composition. With regard to yogurt adulteration, NMR can be used to identify the composition of the sample, which has changed, and this could suggest adulterants are present. For example, when water is added to yogurt, dilution leads to detectable changes in lactose and protein levels under NMR analysis [40]. Likewise, introducing non-yogurt sources of milk solids would yield varying spectral patterns that could not be compared with those of real yogurt. The extent of contamination in a sample can also be measured by NMR, which may prove valuable in determining the extent of the issue and possible health hazards to consumers. After comparing the NMR of pure yogurt with that of the adulterated samples, it is possible to come up with the algorithms that can then be used to detect and determine the level of adulteration [41]. The tool of NMR spectroscopy can be effectively used in detecting and quantifying adulteration of yogurt, which can be utilized in ensuring this commonly used dairy product maintains good quality and is safe with respect to its overall principle of working, illustrated in Figure 9.

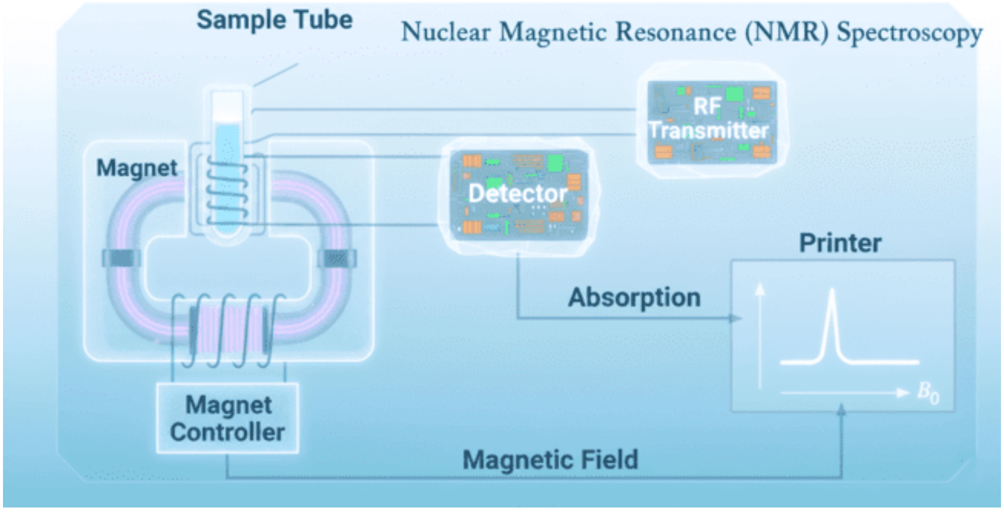
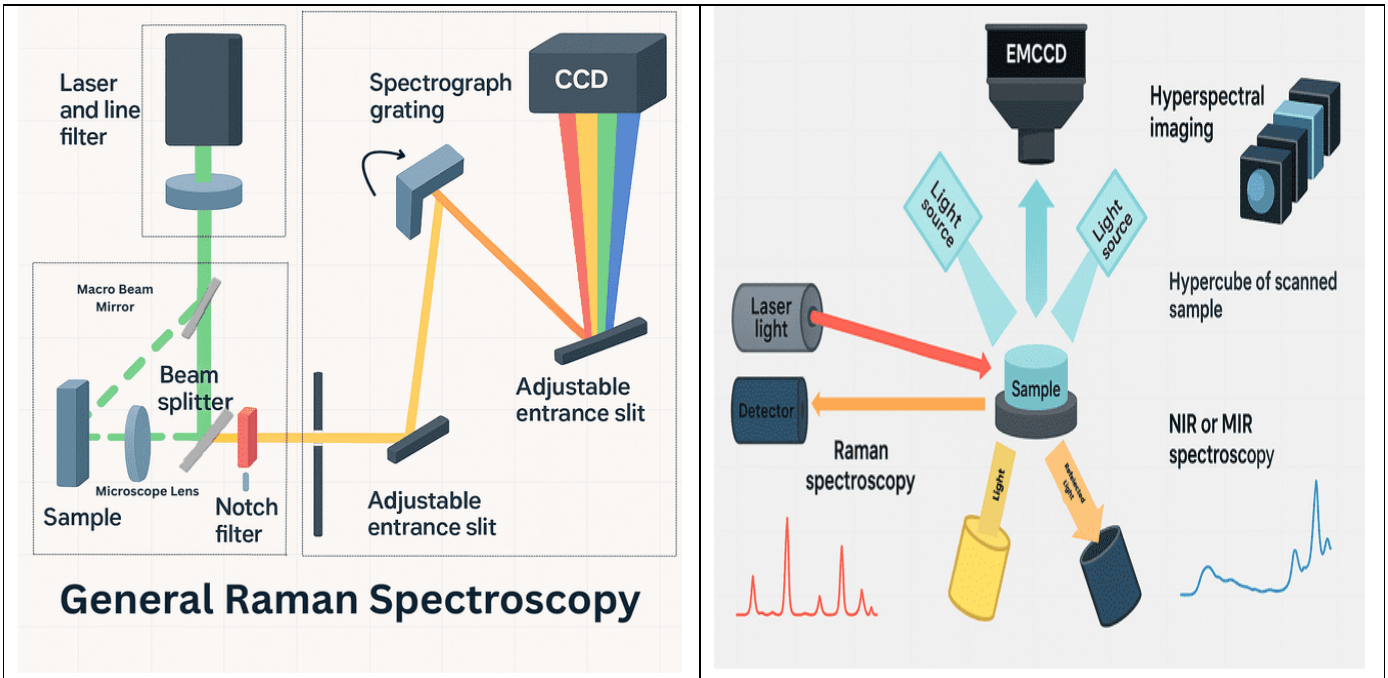


Figure 9. View of Fundamentals of NMR Spectroscopic Method [42].

The NMR spectroscopy method of adulteration of yogurt is a very sensitive and precise method, since the adulteration of yogurt can be found even when a small portion is added to the sample [1]. The process is also quite fast, and a large sample can be analyzed within a relatively short time.

5.4. Raman Spectroscopy RS

Raman spectroscopy (RS) is a very strong analytical spectroscopy method used in determining the character of materials such as solids, liquids, and gases. It is based on the interaction of matter with light, specifically with the scattering of photons; his technique reveals both the molecular architecture and the chemical profile of the material. Raman spectroscopy works by shining a laser light onto a sample and detecting the generated scattered light. The scattered light has a different frequency than the incident light due to interactions with the molecules in the sample [43]. This difference in frequency, known as the Raman shift, is used to generate a Raman spectrum. The pattern and strength of Raman peaks reflect the vibrational modes of chemical bonds, enabling analysis of the molecular structure [44].



a) Raman spectroscopy using a CCD Detector

b) Raman spectroscopy using EMCCD Detector

Figure 10. General methods of Raman spectroscopy [45].

Raman spectroscopy can identify specific chemical compounds and determine the orientation and symmetry of molecules. It can also be used to analyze the crystalline structure of solids and the state of molecules in liquids [46]. There are two main types of Raman spectroscopy: spontaneous and stimulated. Spontaneous Raman spectroscopy uses a single laser beam to excite the sample, while stimulated Raman spectroscopy uses two laser beams to enhance the Raman signal [47]. A major benefit of Raman spectroscopy is its ability to examine materials directly in their native form, eliminating the need for complex preparation steps [48]. Additionally, this technique allows examination without causing physical or chemical changes to the material, making it highly suitable for sensitive analyses. Its principles are illustrated in Figure 10 (a). Raman spectroscopy is a rapid and non-destructive analytical technique that can detect adulteration in yogurt and other food products [11]. However, the analysis requires careful sample preparation and data analysis to ensure reliable results.

5.5. Near Infrared Spectroscopy

Near Infrared Spectroscopy (NIRS) is a non-invasive analytical technique that uses light in the electromagnetic spectrum’s near-infrared region to measure a sample's absorbance, reflectance, or transmittance [49]. Near-infrared (NIR) spectroscopy has gained extensive application within the dairy industry for detailed compositional assessment, as it offers a significantly faster alternative to conventional reference techniques. The method is non-destructive, no chemical reagents are necessary, it has a low impact on the environment, and the sample preparation does not need to be done extensively. The principle of NIR is that molecules absorb electromagnetic radiation between

750-2500 nm wavelength, which is especially applicable in molecules that possess functional groups C-H, N-H, S-H, or O-H bonds [50]. This method is based on the concept that chemical bonds and functional groups contained in a material have characteristic light absorptions at a certain wavelength. One can then study these specific absorption patterns to determine not only the chemical constituents of the sample, but also to determine the chemical quantities of those components. The overall working principle of NIRS is shown in Figure 11.

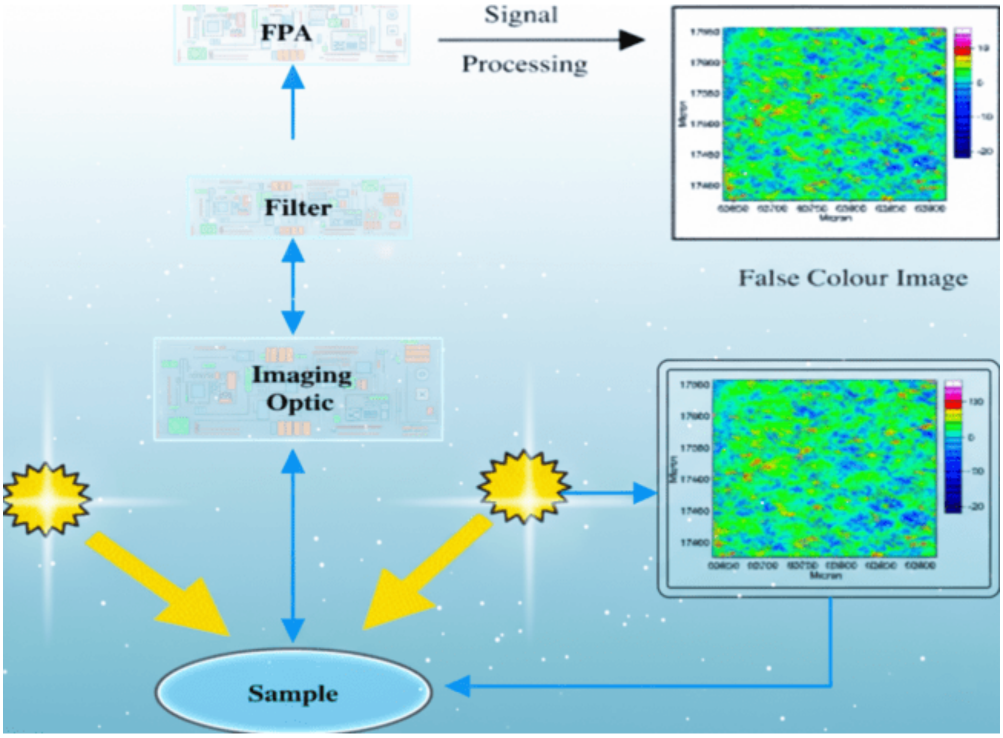


Figure 11. General Method for Adulterating Using NIRS [51].

Many studies use sensory evaluation techniques to determine adulteration of dairy products. Sensory analysis is a collection of systematic methods aimed at correctly interpreting human senses in response to food with minimal inherent biases [52]. NIRS has a wide range of applications, which include agriculture, food science, pharmaceuticals, and biomedical research. NIRS is applied in agriculture, e.g., to determine the chemical content of plants and soil; to assess plant growth and development. Near-infrared spectroscopy (NIRS) has been extensively applied in food science to determine the quality and safety of foodstuffs, such as measuring fat, protein, and moisture content in meat, milk products, and cereal grains [53]. Table 2 summarizes applications of NIR spectroscopy in the detection of adulteration in dairy. NIRS is used in the pharmaceutical industry to test the quality and purity of chemical compounds and to quantify the concentration of active compounds in a prescription.

Table 2. Near-Infrared (NIR) Spectroscopy Applications for Identifying Adulteration in Dairy Products.

Matrix (dairy)	Adulterant/Target	Instrument/Modality	Acquisition mode	Spectral window	Chemometric approach	Ref.
Cheese (assorted types)	Milk-species discrimination (cow/ewe/goat)	Near-Infrared Spectroscopy (NIR)	Reflectance	1100–2000 nm	Modified Partial Least Squares (MPLS)	[54]

yogurt	Added fats/oils (margarine, sunflower, corn, hydrogenated veg.)	Fourier Transform Near-Infrared Spectroscopy (FT-NIR) or Fourier Transform Mid-Infrared Spectroscopy (FT-MIR)	Reflectance or Attenuated Total Reflectance (ATR)	10,000–4,000 cm^{-1} or 5,860–4,000 cm^{-1}	Soft Independent Modeling of Class Analogy (SIMCA); Partial Least Squares Regression (PLSR)	[55]
Clarified butter (ghee)	Tallow	Near-Infrared Spectroscopy (NIR)	Reflectance	10,000–4,000 cm^{-1}	Principal Component Analysis (PCA); Partial Least Squares Discriminant Analysis (PLS-DA); Partial Least Squares Regression (PLSR)	[43]
Cheese (assorted types)	Milk-species discrimination (cow/ewe/goat)	Near-Infrared Spectroscopy (NIR)	Reflectance	1100–2000 nm	Principal Component Analysis (PCA); Modified Partial Least Squares (MPLS)	[56]
Ezine cheese	Bovine/caprine/ovine milk differentiation	Near-Infrared Spectroscopy (NIR)	Diffuse reflectance	10,000–4,000 cm^{-1}	Principal Component Analysis (PCA); Partial Least Squares Regression (PLSR)	[57]
Emmental cheese	Geographical origin	Near-Infrared Spectroscopy (NIR) or Mid-Infrared Spectroscopy (MIR)	Diffuse reflectance / Transmittance	10,000–4,000 cm^{-1} or 3,000–2,800 cm^{-1}	Principal Component Analysis (PCA); Fisher Discriminant Analysis (FDA); Common Components and Specific Weights Analysis (CCSWA)	[58]
Ricotta cheese	Non-milk fat; added water; non-milk protein	Near-Infrared Spectroscopy (NIR)	Diffuse reflectance	1100–2500 nm	Principal Component Analysis (PCA); Partial Least Squares Regression (PLSR)	[59]
Zamorano cheese	Regulatory non-compliance	Near-Infrared Spectroscopy (NIR)	Transmittance	850–1050 nm	Partial Least Squares Regression (PLSR)	[60]
Grated Parmigiano-Reggiano	Admixture with other dairy product(s)	Fourier Transform Near-Infrared Spectroscopy (FT-NIR)	Reflectance	1064–1335 nm / 1933–2357 nm	Principal Component Analysis (PCA); Partial Least Squares Regression (PLSR)	[61]
Long-ripened cheeses	Mislabeling of ripening age	Near-Infrared Hyperspectral Imaging (NIR-HSI)	Line-scan	937–2542 nm	Partial Least Squares Discriminant Analysis (PLS-DA); Partial	[62]

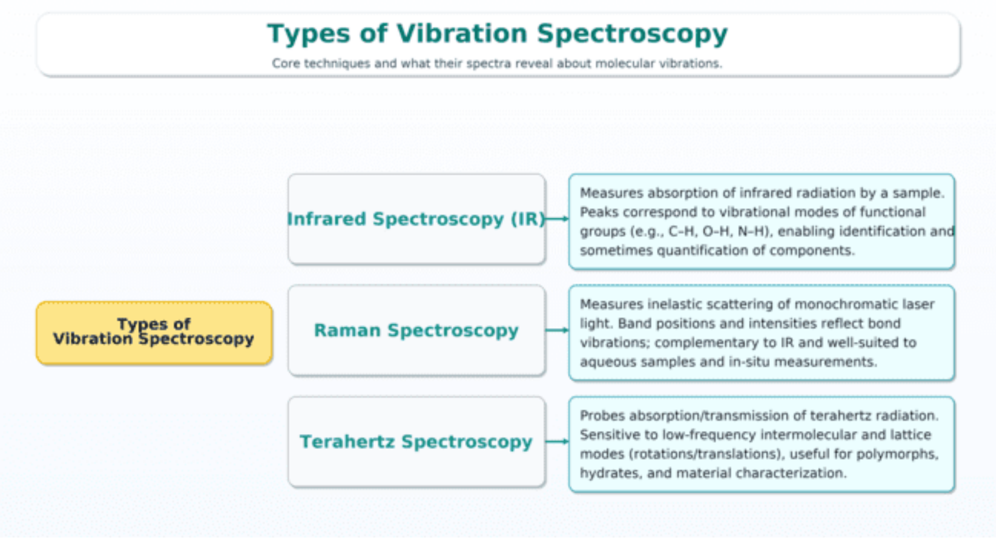
					Least Squares Regression (PLSR)	
Grated Parmigiano-Reggiano	Presence of rind	Near-Infrared Hyperspectral Imaging (NIR-HSI)	Line-scan	900–1700 nm	Principal Component Analysis (PCA); Partial Least Squares Regression (PLSR)	[63]
Grated cheese	Anti-caking/foreign material (MCC, SiO_2, wheat flour/semolina, sawdust)	Fourier Transform Near-Infrared Spectroscopy (FT-NIR)	Reflectance	10,000–4,000 cm^{-1}	Principal Component Analysis (PCA); Partial Least Squares Discriminant Analysis (PLS-DA)	[64]
Goat-milk cheese & yogurt	Cow-milk addition	Fourier Transform Near-Infrared Spectroscopy (FT-NIR)	Transflectance (yogurt); diffuse reflectance (cheese)	10,000–4,000 cm^{-1}	Principal Component Analysis (PCA); multivariate control charts; Partial Least Squares Discriminant Analysis (PLS-DA); interval Partial Least Squares (iPLS)	[65]
Asiago d'allevo cheese	Origin & production attributes	Near-Infrared Spectroscopy (NIR)	—	1100–2500 nm	Principal Component Analysis (PCA); Partial Least Squares Regression (PLSR); Partial Least Squares Discriminant Analysis (PLS-DA)	[66]
Butter, Cheddar & dairy spreads.	Partially hydrogenated oils (industrial trans-FA)	Near-Infrared Spectroscopy (NIR); Fourier Transform Mid-Infrared Spectroscopy (FT-MIR); Raman Spectroscopy	Reflectance / Attenuated Total Reflectance (ATR)	400–2498 nm; 698–4,000 cm^{-1}; 200–2,000 cm^{-1}	Principal Component Analysis (PCA); Partial Least Squares Regression (PLSR)	[67]
yogurt	Variety misclassification	Visible/Near-Infrared Spectroscopy (Vis/NIR)	Reflectance	400–1000 nm	Principal Component Analysis (PCA); Back-Propagation Artificial Neural Network (BP-ANN)	[68]
Cheddar cheese	Brand discrimination	Near-Infrared Hyperspectral Imaging (NIR-HSI)	Line-scan	950.35–1654.15 nm	Partial Least Squares Discriminant Analysis (PLS-DA); Linear Discriminant Analysis (LDA); Successive Projections	[69]

					Algorithm–Linear Discriminant Analysis (SPA-LDA)	
Fresh cheese	Corn flour (starch)	Hyperspectral Imaging (HSI)	Line-scan	200–1000 nm	Partial Least Squares Regression (PLSR)	[70]
Butter	Regulatory non-compliance	Near-Infrared Spectroscopy (NIR)	Reflectance	400–2500 nm	Multiple Linear Regression (MLR); Principal Component Regression (PCR); Modified Partial Least Squares (MPLS)	[71]
Butter	Regulatory non-compliance	Near-Infrared Spectroscopy (NIR)	Reflectance	540–2250 nm	Principal Component Analysis (PCA); Partial Least Squares Regression (PLSR)	[72]
Butter oil	Soybean oil	Fourier Transform Near-Infrared Spectroscopy (FT-NIR) / Fourier Transform Mid-Infrared Spectroscopy (FT-MIR)	Reflectance / Absorbance	12,000–4,000 cm^{-1}; 4,000–400 cm^{-1}	Principal Component Analysis (PCA); Partial Least Squares Regression (PLSR)	[73]
Ewe's cheese	Production-system differentiation	Near-Infrared Spectroscopy (NIR)	Reflectance	1100–2000 nm	Discriminant Partial Least Squares (DPLS)	[74]
Butter	Plant/animal oils (palm kernel, bean, sunflower, linseed, fish)	Near-Infrared Spectroscopy (NIR)	—	6,400–5,100 cm^{-1}	Principal Component Analysis (PCA); Partial Least Squares Discriminant Analysis (PLS-DA); Partial Least Squares Regression (PLSR)	[75]
yogurt	Edible/industrial gelatin; soy protein powder	Near-Infrared Spectroscopy (NIR)	Diffuse reflectance	12,000–4,000 cm^{-1}	One-Class Partial Least Squares (OC-PLS)	[76]

The benefits of NIRS are that it is non-destructive, that is, you can analyse intact samples without the necessity of sample preparation; it is fast and provides precise resolutions [77]. All NIRS systems typically have a light source, a sample holder, a spectrometer, and a detector, and the data acquired can be processed using chemometric techniques, including principal component analysis (PCA) and partial least squares regression (PLS). NIRS is an analytical method that is flexible and has a wide variety of applications in research, industry, and quality control [78]. Depending on the type of adulterants under examination, the interpretation of the results is dependent on the specific adulterant. In this case, when we discover after analysis that no added sugars were present in the real yogurt, then it might mean we are being adulterated with added sugars [79]. NIRS is an effective and fast analytical method capable of detecting adulteration in yogurt and other food products. The quality of the results is, however, subject to the quality of the calibration model and the choice of the right wavelengths to use during the analysis [80]. The preparation of the sample should also be consistent and the instrument properly calibrated at the appropriate point prior to analysis.

5.6. Vibration Spectroscopy

Vibration spectroscopy is a class of analytical techniques that measure the absorption, transmission, or scattering of electromagnetic radiation by a sample as a function of the sample's vibrational motion [81]. The interaction between electromagnetic radiation and the sample is related to the sample's molecular structure, allowing the identification and quantification of various chemical and biological species. Different types of vibration spectroscopy are summarized in Figure 12. There are several types of vibration spectroscopy, each with applications in chemistry, biology, material science, and medicine. For example, IR and Raman spectroscopy are used in chemistry to analyse chemical compounds, including organic and inorganic compounds and polymers [82]. Vibration spectroscopy is used in biology to analyse proteins, lipids, and nucleic acids. In the field of medicine, it is used to diagnose and detect diseases, including cancer. Vibration spectroscopy is an effective analytical method to give useful data concerning the chemical and biological structure of samples. The choice of the best technique is determined by the sample and application in question [83]. This is because the results are dependent on the adulterants one is testing. Indicatively, the occurrence of absorption peaks associated with added sugar can show adulteration in yogurt.



Measures absorption of infrared radiation by a sample. Peaks correspond to vibrational modes of functional groups (e.g., C–H, O–H, N–H), enabling identification and sometimes quantification of components.

Measures inelastic scattering of monochromatic laser light. Band positions and intensities reflect bond vibrations; complementary to IR and well-suited to aqueous samples and in-situ measurements.

Probes absorption/transmission of terahertz radiation. Sensitive to low-frequency intermolecular and lattice modes (rotations/translations), useful for polymorphs, hydrates, and material characterization.

Figure 12. Vibration spectroscopy Types.

Vibration spectroscopy is a viable and effective analytical method that identifies contamination in yogurt and other foods [1]. The results, however, would be as accurate as the quality of the reference spectra and the correct choice of spectral regions to be used in such analysis [84]. The sample preparation also needs to be consistent, and the instrument needs to be well calibrated before analysis..

5.7 UV-Vis Spectroscopy

UV-Vis spectroscopy refers to a form of absorption spectroscopy by which ultraviolet and visible light offer information on the electronic and molecular structure of a sample [85]. This is a common method of determining the concentration and identity of molecules in a sample used in chemistry, biochemistry, and molecular biology. In UV-Vis spectroscopy, the sample is subjected to UV or visible light, and the intensity amplitude of the transmitted light is quantified with respect to the wavelength. The 581 spectrum of the result reveals that the intensity of light the sample absorbs at the same time (at each wavelength) [86]. Types of chemical bonds or chromophores in the sample, and the concentration of the analyte, can be identified using the spectrum.

The simple parts of a UV-Vis spectrometer are a light source, a monochromator for wavelength selection, a sample compartment, and detection. The cuvette containing the sample is placed in the reference cell, and the detector is used to measure the transmitted light intensity. The spectrometer can be calibrated using a standard sample of the concentration to be determined, and then the absorbance reading at a wavelength of interest can be obtained [87]. The general mode of operation of UV-Vis spectroscopy is shown in Figure 13.

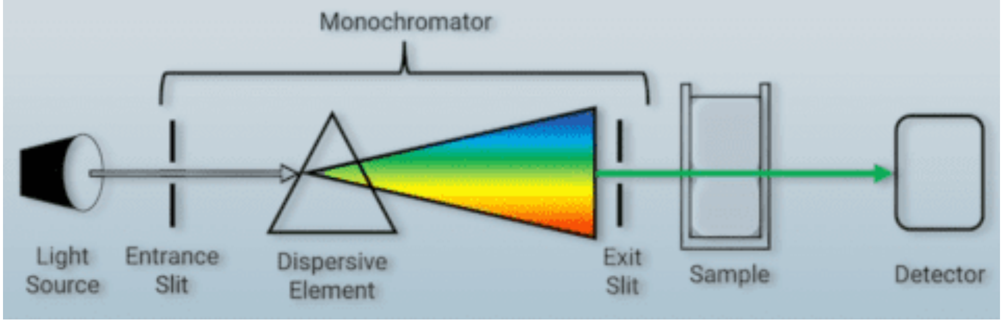


Figure 13. Basic working principle of UV–Vis spectroscopy [88]**.**

Some of the most common applications of UV-Vis spectroscopic analysis are the characterization of DNA, proteins, and other biomolecules, and the determination of metal ions and other chemical species. In biological applications, for example, UV-Vis spectroscopy and absorbance at a specific wavelength are usually applied to calculate the concentration of a protein or DNA sample [89]. The absorbance of the sample is often related to the concentration of the analyte through the Beer-Lambert law in these types of analyses. Ultraviolet-visible (UV-Vis) spectroscopy is a versatile analytical technique that can give information about the electronic and molecular structure of a sample [90]. The method is relatively straightforward, and the sample is not very difficult to prepare, so it is widely used for many applications. Other adulterants in yogurt (i.e., added sugars or starches), which could potentially not influence on protein concentration of a sample, and might therefore need a different analytical approach [91]. A further separation of the adulterants by chromatography or mass spectrometry is necessary [92]. Ultraviolet-visible (UV-Vis) spectroscopy has been applied to measure the protein level of yogurt samples and is a rather easy and convenient method to detect adulteration. However, to guarantee that the analytical conditions are the same (calibration of the instrument and preparation of the samples) for a correct result, it is desired to use a reference value from a properly characterized authentic sample [93].

5.8. Hyperspectral imaging (HSI)

Hyperspectral imaging (HSI) is an advanced analytical technique that combines traditional imaging with spectroscopy to collect and analyze information from across the electromagnetic spectrum. Unlike conventional imaging, which captures only three broad bands of visible light (red, green, blue), HSI records reflectance or absorbance data across hundreds of narrow, contiguous wavelength bands, typically spanning the ultraviolet (UV), visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) regions[94]. The general working principle of adulteration using hyperspectral imaging is illustrated in Figure 14.

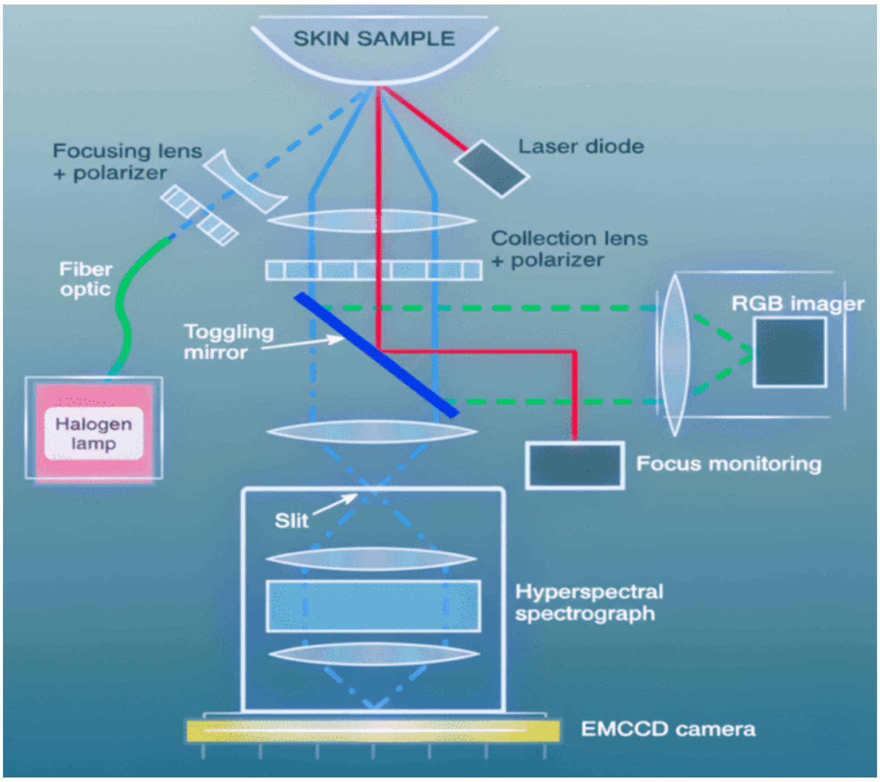


Figure 14. Hyperspectral-Based Imaging Method [95].

Applications of AI, hyperspectral imaging, and spectroscopic techniques in detecting food adulteration, including dilution, substitution, added sugars, and synthetic additives across various products, are illustrated in Figure 15. By extracting distinctive spectral fingerprints and pairing them with machine-learning models, these approaches enable rapid, often non-destructive screening and classification, improving sensitivity and throughput compared with conventional assays.

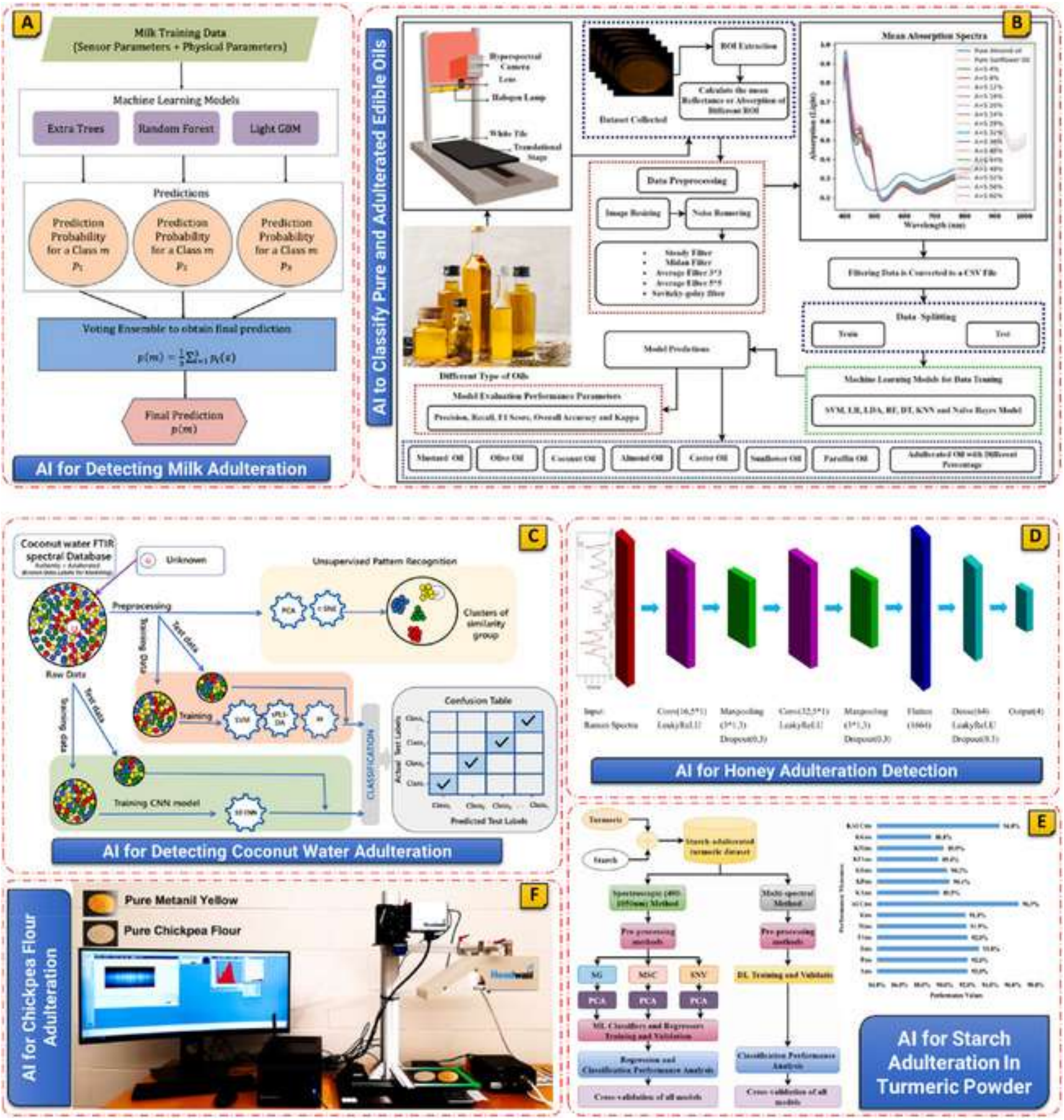


Figure 15. Applications of AI, hyperspectral imaging, and modern spectroscopy for detecting food adulteration in milk, edible oils, coconut water, honey, turmeric powder, and chickpea flour [96].

In practice, HSI systems use specialized cameras or line-scanning sensors to acquire images, where each pixel in the image contains a complete spectrum. The result is a three-dimensional dataset known as a hypercube or data cube, with two spatial dimensions (x, y) and one spectral dimension (λ). This structure allows simultaneous extraction of both spatial and spectral information, enabling the identification, classification, and quantification of materials based on their unique spectral signatures. Once captured, hyperspectral images undergo several processing steps, including calibration, noise reduction, and correction for illumination effects. Advanced chemometric and machine learning algorithms are then applied to extract relevant features, perform classification, or detect anomalies within the sample. Because every material exhibits characteristic absorption or reflection patterns at specific wavelengths, HSI provides a rapid and non-destructive way to distinguish between authentic and adulterated samples.

HSI has applications across multiple domains. In remote sensing, it is used for land cover classification, vegetation mapping, and environmental monitoring. In agriculture, it enables non-invasive monitoring of crop health, early detection of diseases, and precision farming. In geology and mineral exploration, it assists in identifying surface mineralogy and detecting hidden geological structures. Beyond these, HSI has also been applied in fields such as biomedicine, defense, and archaeology, for example, detecting buried artifacts or revealing hidden features in ancient manuscripts [97].

6. Conclusion

Yogurt adulteration remains a practical and scientific challenge: it dilutes nutritional value, alters sensory quality, and may jeopardize safety. This article reviews yogurt adulteration detection via THz, LIBS, NMR, Raman, NIR, mid-IR/FTIR (vibrational), UV–Vis, and HSI. Taken together, these modalities offer complementary strengths: NIR/Raman/FTIR provide sensitive chemical fingerprints for common extenders and sweeteners; HSI adds spatial mapping to reveal heterogeneous or localized adulterants; LIBS targets elemental residues; THz probes bulk structure and water binding; NMR delivers compositional profiling; and UV–Vis remains a low-cost option for chromophoric additives, albeit with lower specificity. When coupled with chemometrics and modern AI, their classification and quantification performance improves substantially, enabling rapid, non-destructive screening suited to at-/inline quality control. Remaining barriers include fermentation-driven matrix variability, texture-related scattering, calibration transfer across instruments and sites, and the scarcity of open, standardized datasets. We therefore recommend multi-modal data fusion (e.g., HSI+Raman/LIBS), portable platforms with on-device inference, interpretable models with uncertainty reporting, and harmonized sampling and preprocessing protocols to achieve reliable, routine surveillance of yogurt authenticity across the dairy supply chain.

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The authors declare they have no conflicts of interest to report regarding the present study.

Conflict of Interest

The Authors declare that they have no conflicts of interest to report regarding the present study.

Author Contributions

Conceptualization and review design, M.A., M.N., and H.S; methodology, M.A; reference-management tooling, S.A; validation of screening and inclusion/exclusion criteria, M.A, H.S, and U.S; formal analysis and synthesis, A.R. and U.S.; investigation (literature search and data extraction), M.N.; resources, U.S and S.A; writing original draft preparation, M.A; writing review and editing, M.A; visualization (figures and summary tables), H.S.; supervision, M.A; project administration, S.A; funding acquisition, M.N. All authors have read and agreed to the published version of the manuscript.

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