Applications of Raman spectroscopy in food safety and quality control

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Abstract

Background and objective: In response to the escalating demand for food products, the assessment of quality and safety has become paramount for regulatory authorities, industry stakeholders, and consumers. This review comprehensively examines the applications of Raman spectroscopy in food evaluation, focusing on its efficacy in detecting food adulteration, unauthorized additives, antibiotics, drugs, residues of pesticides, fungicides, and heavy metals.

Results and conclusion: While conventional analytical techniques often suffer from issues such as time consumption, high costs, destructiveness, and dependence on the skilled personnel, there is a collective effort in the scientific community to explore innovative diagnostic approaches. Among the growing methodologies, Raman spectroscopy has emerged as a promising candidate due to its simplicity, rapidity, non-destructiveness, and high accuracy. Furthermore, it investigates its utility in identifying foodborne pathogenic microorganisms. Drawing insights from diverse research reports, this study highlights Raman spectroscopy as a potent tool for monitoring and ensuring food quality and safety. As advancements continue to be revealed, it is anticipated that the industrial application of this method will witness significant growth in the future.

Keywords: Adulteration, Food Safety, Quality control, Raman Spectroscopy

1. Introduction

In recent decades, the escalating concern over food safety has increased attention, driven by the presence of hazardous compounds such as pesticides, illegal additives, antibiotics, pathogenic bacteria, and various adulterants. These pose significant threats to human health [1,2]. The urgency to address these concerns has created a demand for effective methods to identify and quantify these factors. While traditional analytical techniques like chromatography, voltammetry, and biological assays have demonstrated accuracy and reliability, their widespread acceptance is limited by prolonged sample preparation processes and complex testing methodologies [3].

In response to these challenges, there has been a concerted effort to integrate rapid, accurate, and non-destructive methodologies into food safety and quality assessment. Spectroscopy methods, in particular, have emerged as promising techniques to meet these imperatives[4]. The non-invasive and non-destructive nature of spectroscopy, coupled with its capacity for rapid and precise analyses, positions it as a compelling alternative to conventional methods. This shift towards spectroscopy aligns with the current imperative to simplify testing processes, reduce wasting time, and reduce financial costs associated with food safety assessments. As this transition unfolds, it is essential

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to explore and validate the efficiency of spectros-copy methods across diverse food matrices and potential contaminants, paving the way for their integration into typical food safety protocols.

Spectroscopy includes various methods grounded in emission, absorption, fluorescence, or scattering phenomena, is extensively employed for the characterization of diverse samples, offering both qualitative and quantitative insights [5]. Qualitative analyses serve to identify sample composition, while quantitative analyses facilitate the determination of analyte concentrations within the sample matrix. Among these spectroscopic metho-dologies, Raman spectroscopy, named after its pioneer Chandrashekhar Venkata Raman, stands out. The innovative work on this technique was presented by Raman and Krishnan in their pioneering article [6]. Raman spectroscopy invol-ves the irradiation of samples with monochromatic visible or near-infrared light emitted by a laser. This method applies to liquid, solid, and gaseous samples, providing unique information related to structural alterations in the samples [7,8]. The flexibility of Raman spectroscopy, covering a wide range of sample states, positions it as a potent instrument for revealing the structure of diverse materials.

In the subsequent sections, this review establishes a clear link between different aspects outlined in the text, starting with a detailed exploration of the basics of Raman spectroscopy. The focus then shifts to recent developments in its application within the realm of food safety and quality control. By examining its role in observing adulterants, it detects traces of antibiotics, drugs, pesticides, fungicides, and heavy metals, and uncover unauthorized additives in food. Additionally, the study investigates how various Raman spectros-copy methods contribute to the identification of harmful microorganisms in food. The present review seeks to explore recent advancements in the application of Raman spectroscopy in specific food materials, aiming to provide a comprehensive overview of its potential role in ensuring food safety and quality control. Through the examination of developments in this field, the review aims to under-score the significant contributions of Raman spectros-copy in the context of food safety and quality assurance.

2. Raman spectroscopy

Vibrational spectroscopy involves the transfer of energy between the vibrational energy levels of a molecule. This spectroscopic technique is rooted in absorption, transmission, and scattering phenomena that occur when electromagnetic radiation interacts with a molecule. While absorption and transmission are associated with the infrared spectrum, Raman spectroscopy relies on the principle of scattering, known as Raman scattering [9].

2.1. Theoretical foundations

In Raman spectroscopy, a monochromatic laser beam is directed to the sample, leading to interactions with the sample molecules and scattering in multiple directions. The majority of the scattered photons exhibit elastic behavior, possessing the same energy and wavelength as the incident photons, a pheno-menon referred to as Rayleigh scattering. A small fraction of the scattered photons, however, undergo inelastic scattering, resulting in distinct energy and wavelength compared to the incident photons; this constitutes Raman scattering. Raman scattering is further categorized into two types based on the disparity in energy or wavelength compared to the incident photons: Stokes Raman and anti-Stokes Raman (Figure 1).
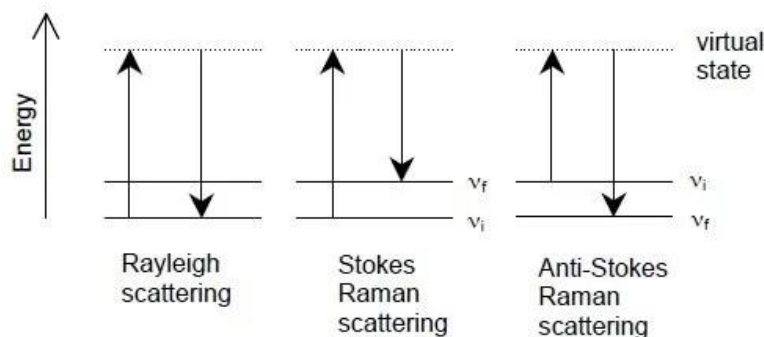
Figure 1. Energy level diagram demonstrating Raman scattering

Stokes Raman occurs when the energy of the incident photon is greater than that of the scattered photon, with a shorter wavelength. Conversely, anti-Stokes Raman is observed when the energy of the incident photon is lower than that of the scattered photon, corresponding to a longer wavelength [10,11].

Stokes Raman bands, occurring in vibrational energy transitions from lower to higher levels, exhibit higher intensity compared to Anti-Stokes Raman bands, which involve transitions from higher to lower energy levels. Consequently, Raman spectroscopy predominantly focuses on investigating Stokes Raman phenomena. Generally, the efficacy of Raman scattering is dependent on the wavelength of the incident light, and achieving the Raman spectrum necessitates inducing a polarization change during molecular vibrations [12]. A typical laboratory Raman spectrometer comprises four essential components: a laser light source, a sampling system, a detection system, and a computer for data acquisition and storage. The laser light is directed onto the sample through an optical microscope, initiating Raman scattering. Subsequently, the Raman scattering photons are collected in a spectrometer after passing through suitable filters. The resulting spectrum of the sample is then displayed in relevant software [13].

2.2. Raman spectroscopy techniques

Raman spectroscopy, a potent analytical tool, encompasses a range of techniques pivotal for the examination and interpretation of molecular structures. This section delves into the fundamental Raman spectroscopy techniques employed in food analysis. Table 1 provides a summary of the distinctive benefits associated with these techniques [14].

Table 1- Advantages of different Raman spectroscopy techniques

Technique	Advantages
Dispersive Raman spectroscopy	• Can be used for liquid samples, with high temperature (up to 1000 °C) and black samples. • Absence of fluorescence in the wavelength of 780 to 830 nm
Fourier Transform Raman Spectroscopy (FT-Raman)	• Reduction of fluorescence • Improved image resolution
Surface-Enhanced Raman Scattering (SERS)	• High resolution and sensitivity
Spatially Offset Raman Spectroscopy (SORS)	• Less fluorescence • Facilitating the analysis of samples

2.2.1. Dispersive Raman spectroscopy

Dispersive Raman spectroscopy represents the most prevalent and fundamental method, utilizing high-intensity monochromatic radiation typically emitted by continuous-wave gas lasers like argon, krypton ions, or diodes. Dispersive Raman spectroscopy boasts inherent advantages: (1) its compatibility with aqueous-phase samples; (2) applicability to samples at elevated temperatures, surpassing 1000 °C; (3) its ability to analyze black samples; and (4) the use of a 780 or 830 nm laser aids in mitigating sample fluorescence [14].

2.2.2. Surface-Enhanced Raman Scattering (SERS)

SERS enhances Raman signals through the interaction of analytes with metallic nanostructures, commonly gold or silver nanoparticles. This technique boosts sensitivity, proving invaluable for trace analysis in intricate food matrices. The application of SERS in detecting contaminants and characterizing molecular structures contributes to its growing prominence in studies related to food safety [15].

2.2.3. Fourier Transform Raman Spectroscopy (FT-Raman)

Fourier transform Raman spectroscopy (FT-Raman) employs interferometry to swiftly obtain Raman spectra with high resolution. This technique enhances signal-to-noise ratios, rendering it suitable for analyzing weak Raman signals within challenging food matrices. Widely utilized in quantitative analysis and quality control, FT-Raman stands out for its precision and efficiency [16].

2.2.4. Spatially Offset Raman Spectroscopy (SORS)

Spatially Offset Raman Spectroscopy (SORS) facilitates non-invasive analysis of subsurface layers within opaque or turbid samples. By manipulating the spatial offset between the incident laser and the Raman collection point, SORS provides depth-resolved information. This techni-

que proves valuable in assessing the internal composition of food products without necessitating sample preparation [17].

3. Processing of Raman spectral data

3.1. Data preprocessing techniques

Chemometric methods serve as potent tools in vibrational spectroscopic techniques, enabling the rapid and reliable analysis of analyte spectral data. To harness the capabilities of these processing methods, it is imperative to preprocess the data for optimization [18]. In addition to the spectral information acquired from food samples, the chemical profile may encompass irrelevant components such as fluorescence background, stray light, detector noise, device noise, and laser power vibration, introducing noise and irrelevant data. Consequently, the main key for data analysis lies in the preprocessing of the Raman device-generated spectrum. Techniques such as smoothing, light scattering correction, baseline correction, and normalization are employed for this purpose [19].

3.2. Feature extraction strategies

Following data preprocessing, the subsequent step involves feature extraction, which has an important relationship with spectral data mining. Significantly, enhancing the performance and predictive capacity of the model is often achievable by judiciously selecting suitable features and discarding irrelevant or weakly correlated ones. Researchers in data mining employ diverse methods for feature extraction, with the overall advantage of reducing overfitting, elevating prediction accuracy, saving time, and optimizing computing resources [20]. This approach to Raman spectral data processing not only ensures the extraction of meaningful information but also contributes to the refinement and efficiency of predictive models.

3.3. Chemometrics models development

The final stage of Raman spectral data analysis involves the development of chemometrics models. The molecular vibrations reflected in the Raman spectrum of food generate complex information,

presenting challenges in the analysis of the spectrum as a whole. Therefore, the creation of chemometrics models becomes crucial at this point, allowing for the separation and extraction of specific information from the complex or over-lapping data within the Raman spectrum. This strategic use of chemometrics significantly enhan-ces the overall Raman spectrum analysis process.

Chemometrics, in achieving three primary objectives-data description, qualitative analysis (discrimination, classification, clustering), and quantitative analysis (regression and prediction)-plays a crucial role in interpreting the complicated information summarized in Raman spectra. Spectral data, characterized by their complexity, are commonly managed through the application of chemometric methods, which encompass both supervised and unsupervised pattern recognition techniques. Notable approaches include hierar-chical cluster analysis (HCA), principal component analysis (PCA), linear discriminant analysis (LDA), soft independent modeling of class analogy (SIMCA), and partial least squares-discriminant analysis (PLS-DA), among others. These tools primarily serve to evaluate sample classes, distinguishing between characteristics such as adulteration status (adulterated/unadulterated) or authenticity (authentic/not authentic).

In addition to qualitative chemometric methods, quantitative approaches play a significant role, involving the utilization of multivariate calibration tools. This includes techniques like principal component regression (PCR) and partial least squares (PLS), which are pivotal for quantifying parameters such as the number of adulterants and the content of fatty acids. These quantitative tools leverage data generated from spectroscopic techni-ques, contributing to a nuanced and detailed analysis of the spectral information, thus enhancing the capabilities of spectroscopy in both qualitative and quantitative assessments [19]. The utilization of chemometrics in the final stage of Raman spectral data analysis not only improves the interpretability of results but also enhances the

precision and depth of insights garnered from complex molecular vibrational information.

4. Utilizing Raman spectroscopy for food safety and quality assessment

Raman spectroscopy plays a pivotal role in food analysis, primarily aiming to identify compounds and explain structural changes occurring in food during processing. This technique can analyze a spectrum of constituents including external elements such as adulterants and microorganisms, internal minor compounds like synthetic dyes, carotenoids, and compounds migrating from packaging to food, as well as macro compounds encompassing fats, proteins, and carbohydrates. The recent advancements in various components of Raman devices have rendered this methodology an efficient means of accuracy and ensuring the safety and quality of food [21].

4.1. Food adulteration assessment

The adulteration of food, presents a global challenge and pose potential hazards to human health. As reported by the US centers for disease control and prevention (CDC), dairy products stand as the second most prevalent food adulterant following green leafy vegetables, contributing to 14% of all foodborne illnesses. Among dairy products, milk powder is noteworthy because it is a common candidate of adulteration by addition of melamine to increase its protein content, posing severe risk of death among infants [22]. Given the potentially irreparable health consequences associated with such adulteration practices, there is a critical need to fast method to accurately determine these issues. Hence, given the potentially irreversible health impacts of certain adulteration practices, it is critical to quickly and precisely identify them.

In 2009, Okazaki et al. successfully identified melamine in powdered milk without the need for melamine extraction from the milk, utilizing the Raman band at 676 cm^{-1} [23]. In a study conducted by Betz et al. in 2012, a silver Surface-Enhanced Raman Spectroscopy (SERS) substrate was employed for the detection of melamine in infant formula at

concentration of 5 mg/kg. The spectrum was acquired using a diode laser with a wavelength of 785 nm, revealing a melamine peak at approximately 680 cm⁻¹, attributed to deformation observed in the triazine ring [24]. Subsequently, in 2014, Giovannozzi et al. devised a rapid and highly sensitive method for detecting melamine in liquid milk. This innovative approach utilized gold as a SERS substrate, demonstrating significant potential in enhancing melamine signals within the Raman spectrum. As illustrated in Figure 2, the melamine peaks associated with different concentrations of melamine in the spiked samples exhibit clear separation. The method demonstrates favorable responses within the investigated concentration range. Notably, this method resulted in reduction of 30 min in the total analysis time [25].
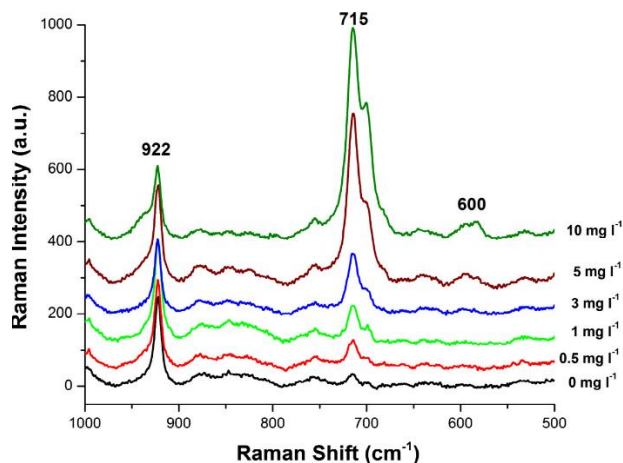

Figure 2- SERS spectra of 40 nm AuNPs with different melamine concentrations in spiked milk samples: 0, 0.5, 1, 3, 5, 10 mg/l

In the dairy industry, some adulterated milk is made of whey, which compromises its nutritional value. In 2011, Almeida et al. investigated the differentiation of adulterated and non-adulterated milk powder samples as well as the identification of types of milk powder (whole, low-fat, non-fat, or modified) by FT-Raman spectroscopy. Chemometrics methods have also been used for data analysis. 100% classification of adulterated samples was obtained with the PLS-DA model and the separation of milk powder samples based on their types was done with the PCA model [26]. Detection of adulteration in butter is also another important issue in dairy products [27-33].

In 2016, Eksi-Kocak et al. devised a quick and non-invasive way to detect the adulteration of pistachio kernels with green peas. They used Raman hyperspectral imaging along with chemometrics for this method [34]. In another investigation, the researchers designed a macro-scale and line-scan Raman imaging system tailored for the comprehensive assessment of diverse food powders and raw materials. They acquired ultra-spectral Raman images spanning the wavelength range of 1102-2865 cm⁻¹ from three pairs of samples and adulterated mixtures at a concentration of 0.5%. The spatial and spectral details obtained from Raman hyperspectral images were leveraged to recognize adulterations within the mixtures of food powders [35]. In 2020, Dai et al. investigated the analytical method to quantify the color strength of saffron and also to identify saffron adulteration using the combination of Raman spectroscopy and thin-layer chromatography.

This developed approach to quantify the color strength of pure saffron and also to distinguish adulterated saffron from pure saffron showed a very good performance [36]. Food adulteration, particularly in the context of honey, presents a significant challenge,

prompting the application of various techniques for assessment and identification. Raman spectroscopy stands out as one such method employed in the evaluation of honey authenticity [37]. In a study conducted in 2002, the investigation focused on detecting the adulteration of honey with sugarcane invert and sugar beet, by using FT-Raman. The findings emphasized the effectiveness of Raman spectroscopy in accurately predicting honey adulteration, achieving $R^2 > 0.91$ among various honey types [38]. In addition, Oroian et al. investigated the presence of fructose, glucose, inverted sugar, hydrolyzed inulin syrup, and malt in honey using Raman, and analyzed the Raman data using PLSR and PCA chemometrics methods. They found that Raman is a simple, fast, and effective method to identify such adulterations in honey [39]. Raman-coupled chemometrics techniques were employed to analyze the honey samples in other studies as well [40-43].

Raman spectroscopy emerges as a promising tool for assessing adulterations in meat and meat products. In 2019, Chen et al. conducted a study on the rapid identification of adulteration practices in Atlantic salmon using Raman spectroscopy in conjunction with machine learning techniques. The findings showed the capability of Raman spectroscopy as a rapid and efficient method for adulteration detection, with the developed model demonstrating effectiveness in quantitative data analysis [44]. Many studies have focused on Raman spectroscopy to detect adulteration in meat and meat products [44-50]. Moreover, there are a lot of studies about the use of Raman spectroscopy for assessing the cooking oils adulteration such as olive oil [51-58].

These applications underscore the multifaceted capabilities and effectiveness of Raman spectroscopy in tackling the intricate challenges linked to the adulteration of food. Its ability to discern subtle changes in molecular composition, even in complex mixtures, positions it as a versatile and powerful technique for ensuring the integrity and safety of food products. Various applications in different food categories affirm Raman spectroscopy as a valuable asset in the ongoing efforts to combat and mitigate the risks associated with food adulteration, contributing to the overall assurance of food quality and safety.

4.2. Assessment of antibiotic and drug residues in food

Antibiotics, widely employed for treating human infections and various bacterial diseases in animal husbandry and aquaculture, have raised concerns regarding the potential development of antibacterial resistance in humans due to residues in food products. Hence, the detection and quantification of antibiotics and drugs in food are critical attempts.

In 2021, Yang et al. utilized a polydimethylsiloxane plasma cavity as a SERS substrate for detecting tetracycline in milk. Their findings revealed that the modified polydimethylsiloxane plasma cavity exhibited high sensitivity to SERS, achieving a limit of detection of 0.28 μg/l and a correlation coefficient of 0.987. The study reported that utilizing the polydimethylsiloxane substrate in SERS for tetracycline detection in milk is a rapid process, taking approximately 10 min, and represents an effective detection method [59]. In 2016, Qiu et al. introduced an innovative SERS substrate by incorporating silver nanoparticles and carbon nanotubes into laminar graphene oxide (GO) membranes. This substrate was employed for the detection of antibiotics in water during the filtration process. The study focused on the detection of three antibiotics of tetracycline hydro-chloride, ampicillin trihydrate, and oxytetracycline hydrochloride by using a portable Raman spectro-meter [60]. Additionally, Zhang et al. conducted a study on the detection of Enrofloxacin, Furazolidone (an antibiotic), and malachite green (an industrial dye) in tilapia fillet [61]. In 2020, Li et al. highlighted the effectiveness of their proposed SERS method in tandem with utilized chemometric algorithms. This approach was deemed a straightforward, rapid, non-destructive, and cost-effective analytical technique compared to existing chemical methods. Specifically, the method demonstrated effectiveness and efficiency

in both quantitative and qualitative analyses of chlortetracycline and oxytetracycline in animal feed. The chemometrics models developed based on spectra from samples spiked with these antibiotics, exhibited robust predictive performance even at low concentrations. Consequently, the method emerges as a promising candidate for comprehensive monitoring aimed at regulating livestock feed chains [62]. Clenbuterol, initially intended for the treatment of lung diseases, is illicitly employed to promote animal growth in the food industry. This unauthorized use may result in trace amounts of clenbuterol remaining in the final products derived from these animals. Consumption of meat and liver from such animals can have harmful effects on human cardiovascular and respiratory health. In 2016, Zheng et al. introduced a 3D paper microfluidic device designed to facilitate SERS immunoassays. Their study revealed that the optimal diagnostic performance was achieved by combining SERS and immunoassay techniques on the Whatman no. 1 filter paper. Utilizing this cost-effective and rapid SERS substrate, the team successfully detected clenbuterol in pig hair, achieving a remarkable detection limit of 0.1 pg/ml [63]. In 2017, Yu et al. introduced a multiplex immunoassay leveraging Raman spectroscopy to simultaneously detect clenbuterol and ractopamine. Their investigation affirmed the reliability and reproducibility of this diagnostic approach, with a limit of detection recorded at 1 pg/ml for both clenbuterol and ractopamine [64]. These studies collectively contribute significant scientific and technical insights, showcasing the potential of Raman spectroscopy as a robust tool for addressing the critical challenges associated with antibiotic and drug residues in food.

4.3. Assessment of unapproved food additives

The incorporation of colors and food additives in food products serves the dual purpose of enhancing both the physical and chemical attributes, as well as making greater consumer acceptance. However,

certain food additives may pose a toxic threat to the consumer's health. In response to such concerns, the World Health Organization and the Food and Agriculture Organization have described a comprehensive list of food additives along with their permissible limits.

In 2018, a study was conducted to investigate four additive dyes (tartrazine, sunset yellow, acid red, and food blue) using conventional Raman and SERS. The Raman spectra of these additives were identified. By using PCA method, limits of detection within the range of 5.3436-79.285 g/µl were obtained [65]. In the broader context, any substance added to food with the intent of enhancing its properties but lacking legal authorization concerning health standards is deemed unauthorized and illegal. Consequently, there is a pivotal need for the identification of such substances, prompting research in this domain to pivot towards rapid and precise methodologies, such as Raman spectroscopy [66]. Notably, Rhodamine B and Rhodamine 6G are organic dyes characterized by high water solubility and cost-effectiveness, commonly employed in textiles, plastics, and the cosmetic industry. Despite being prohibited in food due to their recognized carcinogenicity and harmful impact on human and animal fertility and growth, these additives continue to be illegally employed in the food industry owing to their affordability and intense coloring properties [67]. In 2017, Tian et al. employed a substrate comprised of graphene-based gold nanoparticles to identify Rhodamine B in water and non-alcoholic beverages. This method yielded positive results in substance identification without the necessity for specialized preparation, utilizing the mentioned substrate in conjunction with SERS [68]. In 2015, Li et al. employed Raman spectroscopy in tandem with chemometrics methods to non-destructively detect lead (II) green chromate in tea [69]. Additionally, the colorant Sudan, notable for its distinct properties, underwent comprehensive analysis using Raman spectroscopy across three conventional Raman models, FT-Raman, and SERS. This investigation was complemented by the use of multivariate analytical methods on spices commonly

utilized in cooking [70]. Metanil Yellow, an azo dye, and malachite green, classified as an inorganic dye, are employed to increase the brightness of yellow and green colors in vegetables, respectively. In a study conducted in 2019, Kumar and Santhanam successfully detected Metanil yellow in Sudanese chickpeas and malachite green in green chickpeas and green peppers. The identification was achieved through SERS using a silver-based paper substrate. Notably, the portable SERS and Raman techniques were easily employed in this method for the simple identification of these two dyes [71]. Sulfur dioxide (SO_2) possesses distinct antioxidant and anti-bacterial properties, rendering it a widely utilized food preservative. However, excessive concen-trations of this compound can harmfully impact lung function, magnify asthma

attacks, and contribute to the occurrence of heart attacks. Detecting SO_2 via SERS poses challenges due to the low SERS cross-section of gas molecules and their weak affinity for metal surfaces. In 2018, Li et al. presented a novel approach involving the isolation of a volatile sample from a complex matrix through void sampling technology. Use of this method coupled with headspace (HS) sampling and a paper-based substrate, enabled the facile and rapid identification of SO_2 in wine. The obtained results demonstrated consistency with those derived from the traditional Monier-William's method [72]. There are other studies that investigated the assessment of unapproved food additives [73-76]. Different methods developed by Raman spectroscopy to identify the foods' adulteration have been listed in Table 2.

Table 2. Raman spectroscopy methods for evaluating the authenticity of food products

Food Matrix	Unapproved Additives	Method	Chemometrics technique	Ref.
-	Four different food colorants (food blue, tartrazine, sunset yellow, acid red)	Surface-Enhanced Raman Spectroscopy (SERS)	Improved principal component analysis (PCA)	(65)
1- Anchor Brand Baking Powder 2- Cake 3- Bacardi Superior White Rum	Cocaine Hydrochloride	Raman spectroscopy	Principal component analysis (PCA) and partial least squares regression (PLSR)	(66)
1- Water 2- Non-alcoholic Beverages	Rhodamine B	Surface-Enhanced Raman Spectroscopy (SERS)	-	(68)
Tea	Lead (II) Chrome Green	Raman spectroscopy	Partial least squares (PLS) Successive projections algorithm (SPA)	(69)
Culinary spices	Sudan I	Raman spectroscopy FT-Raman Surface-Enhanced Raman Spectroscopy (SERS)	Principal component analysis (PCA)	(70)
1- Sudanese Chickpea 2- Green Chickpea 3- Green Pepper	Metanil Yellow Malachite Green	Surface-Enhanced Raman Spectroscopy (SERS)	-	(71)
Wine	Sulfur Dioxide (SO2)	colorimetric/Surface-Enhanced Raman Spectroscopy (SERS)	-	(72)
1- Fruity Pebbles Breakfast Cereal 2- Tropical Skittles Candy 3- Powdered Cheese 4- Cheese Products	16 artificial and natural food colorants	Surface-Enhanced Raman Spectroscopy (SERS)	Principal component analysis (PCA)	(73)

4.4. Assessment of pesticides and fungicides in food

Pesticides are extensively employed in modern agriculture, playing a crucial role in disease and insect pest prevention and sustaining agricultural product yields. However, the overuse of pesticides leads to the prolonged presence of residue toxins in vegetables, fruits, and other agricultural produce, posing adverse effects on human health. Conventional methods such as chromatography including gas chromatography-mass spectrometry (GC-MS) and high-performance liquid chromatography coupled with ultraviolet or mass spectrometry have historically been utilized for pesticide identification. Nonetheless, these methods are time-consuming and necessitate complex preparations [62]. In 2012, Li et al. looked for to address the limitations of traditional methods by employing a conventional Raman spectrometer for the identification of chlorpyrifos residue in apples. However, the achieved detection limit of 45 mg/kg was deemed unsatisfactory [77]. Hence, advancements in SERS methods for pesticide detection have been pursued to enhance its capacity for analyzing a spectrum of food samples from simple

to complex matrices. In 2012, Tang et al. aimed to quantify tricyclazole content in paddy rice using SERS with a portable Raman device. Employing tricyclazole standard solutions, the prominent pyridine peak at 1035 cm^{-1} was identified as the target peak, and the tricyclazole peak at 424 cm^{-1} was selected as the analytical peak for constructing the calibration curve. A notable linear correlation between 424-1035 and tricyclazole concentration (R = 0.995) was established in the concentration range of 0.7-0.005 mg/l, with a limit of detection calculated down to 0.002 mg/l concentration. The study reported that, in comparison to high performance liquid chromatography (HPLC), SERS analysis offers relatively accurate and reliable results [78]. In 2020, Tsen et al. delved into the utilization of SERS to detect residues of Dithio-carbamate fungicides in food [79]. The study employed GLancing Angle Deposition (GLAD) to fabricate the SERS substrate, utilizing Ag@Au alloy nanorods for an economical, cost-effective, and rapid detection process. Figure 3 depicts a schematic illustration of a sequential application of GLAD, performed twice in succession, to fabricate an Ag@Au bimetallic nanoalloy structure.
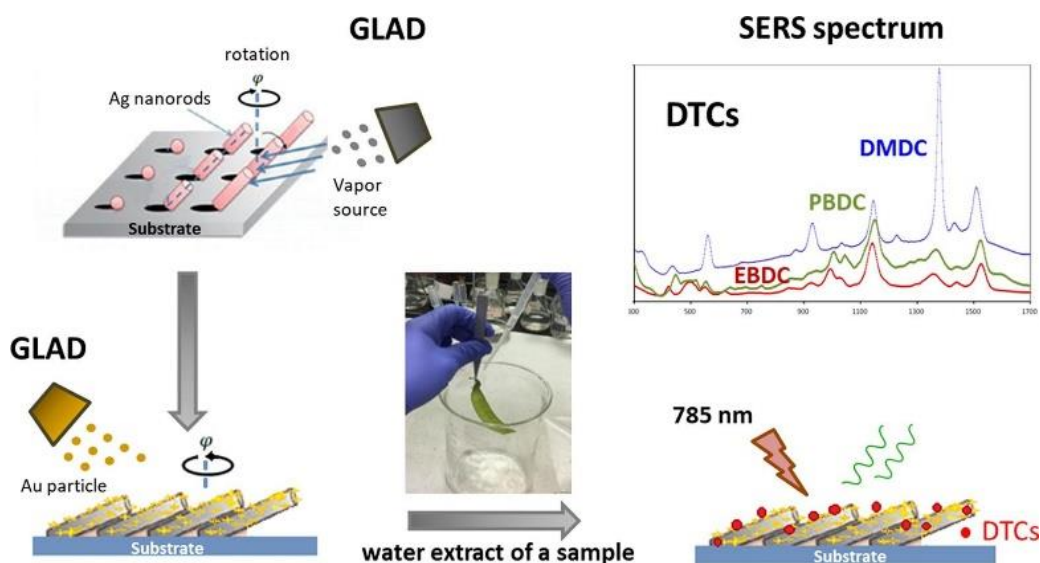

Figure 3- Schematic illustration of a sequential application of GLAD, performed twice in succession, to fabricate an Ag@Au bimetallic nanoalloy structure [79]

This approach was considered an optimal method for extracting residual dithiocarbamate from the surfaces of agricultural products which demonstrated the qualitative and semi-quantitative diagnostic capabilities for three types of dithiocarbamates with the usage of distinctive features of Raman scattering patterns. The proposed method displayed advantages such as simplicity in operation, minimal consumable requirements, heightened safety, and absence of interference in the matrix [79]. In 2020, Ma et al. investigated the detection of Chlorpyrifos pesticide residue on the surface and within the extract of tomatoes using SERS. The results obtained under practical conditions aligned consistently with those derived from standard chlorpyrifos solutions. Linear relationships were established between chlorpyrifos concentration and SERS intensity at critical index peaks in both conditions, demonstrating linearity across the entire measured range from 10^{-3} to 10^{-9} mol/l. The proposed method exhibited a detection limit of 10^{-9} mol/l, significantly surpassing the standards for chlorpyrifos use in China, Japan, and the European Union. The researchers asserted that this method holds considerable promise for the accurate and quantitative detection of pesticide residues in tomatoes and may find applicability across various agricultural products and other domains within food science [80]. In 2018, Lu et al. investigated the impact of the food matrix on SERS signals of pesticides. Their findings revealed that the organic components present in apple juice interfered with the SERS analysis of paraquat [81].

4.5. Assessment of food-borne pathogenic microorganisms

Pathogenic microorganisms transmitted through food or water can induce illnesses in humans, making food-borne diseases a significant public health concern in both developed and developing nations. Consequently, rapid and efficient detection of pathogenic bacteria in food is crucial for ensuring food safety. Conventional approaches to microbial pathogen identification predominantly rely on biochemical methods and specific microbiological diagnostics, presenting challenges in terms of cost-effectiveness and time consumption [82]. Consequently, there is a growing emphasis on the development of rapid, sensitive, and portable diagnostic techniques. Raman spectroscopy has emerged as a notable method offering swiftness and high sensitivity for microbial detection. In a pioneering effort, Yang and Irudayaraj utilized Fourier transform Raman spectroscopy (FTRS) to identify and classify food-origin microorganisms on the surface of whole apples. Achieving 100% accuracy, they successfully distinguished five different species of *Escherichia coli*, highlighting the effectiveness of FTRS as a valuable tool for investigating microbial contamination on food surfaces and selective microbial cultures [16]. Schmilovitch et al. successfully differentiated between samples containing bacteria and those without using Raman spectrometry. Through this Raman method, they specifically identified *Erwinia carotovora pv. carotovora* (ECC) and *Clavibacter michiganense* (CBM) within a concentration range of 10 to 100 cells/ml in a mixed suspension of bacteria [83]. Mizrach et al. achieved optimal detection performance (100%) at the anticipated concentration of 10 CFU/ml of yeast in apple juice using FTRS [84]. In recent decades, the utilization of SERS for the rapid detection of pathogenic bacteria was considered, leading to numerous research in this field [85]. Nevertheless, a majority of SERS diagnostic approaches involve processes such as bacterial-aptamer binding, antibody-bacterial binding, or biological-bacterial ligand binding, each having its distinct set of limitations [86]. In 2018, Yang et al. deposited silver nanoparticles onto electrospun titanium dioxide nanofibers for the direct detection of *E. coli* and *Staphylococcus aureus* without the necessity of aptamers [87]. Subsequently, in 2019, Liao et al. prepared a substrate with the ability to detect and distinguish bacteria, possessing antibacterial properties without requiring chemical modification. The prepared substrate demonstrated special efficacy in bacterial detection in drinking water within a short

time frame of 40 min [88]. Furthermore, in 2015, Cho et al. devised an innovative approach for the identification of *E. coli* O157:H7 in buffalo meat employing membrane filtration and silver enrichment. The aim of this study was the utilization of membrane filtration to concentrate bacteria adhered to nanoparticles. Through this method, the detection of *E. coli* O157:H7 was achieved, even at an exceptionally low concentration of 10 CFU/ml, within a brief period of less than 3 h in buffalo meat [89]. Ilhan et al. (2019) merged a paper-based SERS platform with an immune-enrichment technique, resulting in a specific and rapid diagnostic approach for *E. coli* in milk lower than 1. This method successfully detected 89.6% of *E. coli* in milk, demonstrating a high efficacy. Also, the SERS result obtained was consistent with the conventional planar colony counting method [90].

These investigations emphasize the broad applicability of Raman spectroscopy particularly SERS in promptly and precisely recognizing pathogenic microorganisms in food samples. The demonstrated versatility of Raman spectroscopy as an analytical method underscores its capability to fast identify and describe the existence of harmful microorganisms, providing insights essential for answering the complex challenges linked to ensuring food safety and safeguarding public health.

4.6. Assessment of heavy metals

Heavy metals are present in the soil, water, and atmosphere. These metals can find their way into the food chain through various means, either directly from the environment, human activities such as farming, industrial processes, or vehicular emissions, or through contamination during food processing and storage. Certain heavy metals, like iron, can be intentionally introduced into certain foods for health benefits. However, others, such as arsenic, cadmium, lead, and mercury may have detrimental effects on health [91]. For instance, lead (Pb^{2+}) is of prevalent toxic heavy metals in

food. The accumulation of Pb^{2+} in various organs poses a significant risk to human health, potentially resulting in cancer, mutation, and teratogenesis due to its non-biodegradable nature. Despite the unavoidable presence of Pb^{2+} in food, it is crucial to maintain its concentration below the maximum residue limit (MRL) to safeguard human well-being [92]. Erasmus et al. explored the historical context of food coloration and its influence on product perception, particularly investigating the adulteration of turmeric with hazardous lead chromate. In response to this concern, the researchers developed a spectroscopy-based method for swift detection. By using FT-Raman spectroscopy, they analyzed turmeric samples containing different concentrations of lead chromate. The study successfully detected lead chromate at concentrations of 0.5% or above, demonstrating a limit of detection ranging from 0.5% to 0.6%.[93]. Mercury (Hg^{2+}), a pervasive environmental contaminant among heavy metals, poses potential adverse effects on humans, animals, plants, and aquatic life due to its heightened toxicity and non-biodegradable properties. The proposed approach combines SERS with wavenumber selection chemometrics, utilizing core-shell Au@Ag nanoparticles as the SERS substrate and incorporating Rhodamine 6G as the signaling probe. The complexation initiated by the interaction of Hg^{2+} with citrate ions on Au@Ag NPs results in amalgamation and subsequent desorption of R6G, leading to a decreased SERS signal intensity. Comparative analysis indicates enhanced predictive accuracy when compared to the surface Plasmon resonance method. Favorable recovery rates and precision emphasize the method's capability for predicting Hg^{2+} concentrations in fish and water samples, presenting a valuable tool for quality and safety monitoring.[92]. In a separate study, the identification of cadmium ions in three rice varieties was accomplished through the application of SERS, utilizing gold nanoparticles modified with trimercaptotriazine. This investigation specifically targeted cadmium ions, known for their significant toxicity and potential harm to organs such as the kidneys, liver, and lungs. The methodology involved the chelation of

cadmium ions with trimercaptotriazine, which concurrently interacted with gold nanoparticles. The alterations resulting from this chelation process were discernible through SERS. The developed technique exhibited a detection limit of 8 µg/kg and a quantification limit of 24 µg/kg [94]. Closing remarks, Raman spectroscopy provides auspicious solutions for the swift and precise monitoring of heavy metal concentrations in food, thereby contributing to an improved quality and safety assurance.

5. Conclusion

In conclusion, Raman spectroscopy emerges as a pivotal and precise analytical tool, particularly within the realm of food safety and quality assessment. The continuous progress in electronics, laser technology, optics, and nanotechnology has propelled Raman spectroscopy into a domain of practical and non-destructive applications. Within the critical scope of food safety, Raman spectroscopy's non-invasive and rapid attributes prove highly effective in discerning adulteration, unauthorized additives, and the presence of diverse pathogenic microorganisms, pesticides, and fungicides. These applications directly contribute to the safeguarding of food safety and integrity. Moreover, the strategic integration of Raman spectroscopy with complementary techniques, including near-infrared spectroscopy and other spectroscopic methods, along with the judicious application of chemometrics methods, has introduced this methodology as a promising and alternative paradigm to traditional analytical approaches. This convergence enhances its utility in addressing complex challenges inherent in food safety assessments. The continuous exploration and integration of Raman spectroscopy in food safety protocols are poised to yield advancements that resonate with both scientific rigor and practical applicability. The pivotal role of Raman spectroscopy in shaping the future of analytical methodologies underscores its contribution to a new era of non-invasive, rapid, and accurate analyses crucial for ensuring the safety and quality of food products in diverse and dynamic environments.

6. Conflict of Interest

There are no competing interests to be declared.

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