Typical Raman Spectroscopy Techniques and Their Applications in Agricultural Detection: Research Progress Postprint

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Abstract

Raman spectroscopy is a scattering spectroscopic technique characterized by rapid analysis, insensitivity to water interference, no requirement for sample pretreatment, and capability for in vivo detection, serving as a powerful characterization tool for analyzing and testing the molecular composition and structure of substances. With the continuous development of Raman spectroscopy technology, it has gradually played an extremely important role in the field of agricultural detection. This article outlines the detection principles of Raman spectroscopy, introduces Raman spectroscopy techniques from eight aspects including confocal micro-Raman spectroscopy, Fourier transform Raman spectroscopy, surface-enhanced Raman spectroscopy, tip-enhanced Raman spectroscopy, resonance Raman spectroscopy, spatially offset Raman spectroscopy, shifted excitation Raman difference spectroscopy, and Raman spectroscopy based on nonlinear optics, summarizes the research progress in the application of Raman spectroscopy technology in plant detection, soil detection, water quality detection, food detection, and other areas, and proposes the challenges that need to be addressed and future development directions for its application in the field of agricultural detection, with the aim of providing inspiration for future agricultural production and research.

Full Text

Preamble

Typical Raman Spectroscopy Techniques and Their Applications in Agricultural Detection

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Abstract: Raman spectroscopy is a scattering spectroscopy technique characterized by rapid measurement, minimal water interference, no sample pretreatment requirements, and in vivo detection capabilities. As a powerful molecular-level characterization tool for analyzing material composition and structure, Raman spectroscopy has become increasingly important in agricultural detection domains. This paper outlines the fundamental principles of Raman spectroscopy and introduces eight typical Raman spectroscopy techniques: confocal micro-Raman spectroscopy, Fourier transform Raman spectroscopy, surface-enhanced Raman spectroscopy, tip-enhanced Raman spectroscopy, resonance Raman spectroscopy, spatially offset Raman spectroscopy, shifted excitation Raman difference spectroscopy, and nonlinear optics-based Raman spectroscopy. The paper systematically reviews research progress in applying Raman spectroscopy to plant detection, soil analysis, water quality monitoring, and food safety assessment. Key challenges and future development directions for agricultural applications are identified to inspire future agricultural production and research.

Keywords: Raman spectroscopy; plant phenotyping; plant stress detection; soil detection; pesticide residue detection; water quality detection; food detection

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1 Introduction

Agriculture is a vital industry closely connected to human life and serves as a cornerstone of national economies. Smart agriculture demands more rapid, advanced, and accurate sensors to acquire phenotypic characteristics of crops and livestock, making agricultural production "smarter" and more "intelligent" [1]. The agricultural production chain faces numerous challenges: pesticide residues threaten human health; food adulteration occurs frequently during processing for economic gain. Traditional detection methods require sample pretreatment, are time-consuming, labor-intensive, and destructive. Consequently, developing rapid, non-destructive, and online measurement methods to address these monitoring and detection challenges has become imperative.

In 1928, Indian scientist C.V. Raman discovered the phenomenon of inelastic

light scattering, known as the Raman effect [2]. Raman spectroscopy is obtained based on the Raman effect between excitation light and target molecules, measuring molecular vibrations and rotations. The magnitude of Raman shift is independent of the excitation wavelength, and spectral peak positions reflect characteristic vibrational frequencies of functional groups or chemical bonds in the measured substance. Therefore, Raman spectroscopy is called a "molecular fingerprint." As a powerful molecular detection tool, Raman spectroscopy enables rapid, non-destructive analysis [3-5]. Additionally, water molecules exhibit weak Raman scattering, making Raman spectroscopy less susceptible to water interference and suitable for measuring hydrated biological samples [5]. The measurement principle of Raman spectroscopy is illustrated in [Figure 1: see original paper].

This paper begins with the measurement principles of Raman spectroscopy, summarizes eight typical Raman spectroscopy techniques, reviews research progress in agricultural detection applications, and analyzes existing problems and future development directions.

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2 Overview of Typical Raman Spectroscopy Techniques

Raman spectroscopy signals are extremely weak and were historically limited by low scattering intensity. The technology advanced rapidly only after the 1960s with the advent of laser technology, which significantly enhanced scattering signal intensity. With the maturation of laser technology, optical component fabrication, electronics, nanotechnology, and computing, Raman spectroscopy has evolved into a versatile analytical technique with multiple measurement modalities. This section introduces eight typical Raman spectroscopy techniques.

2.1 Confocal Micro-Raman Spectroscopy

Confocal micro-Raman spectroscopy integrates confocal technology, Raman spectroscopy, and microscopy to perform Raman hyperspectral imaging at micrometer spatial scales, enabling simultaneous analysis of chemical composition and spatial distribution [6]. The confocal configuration with a pinhole enables spatial filtering along the X, Y, and Z (depth) axes, effectively removing stray light and improving signal-to-noise ratio. This technique produces clear images with high spatial resolution and has been widely applied in life sciences research at microscopic scales [6,7].

Long-focal-length Raman spectrometers also provide high spectral resolution, allowing differentiation of more characteristic peaks for complex mixture analysis. However, confocal micro-Raman systems require complex microscopic structures and large optical chambers, making them primarily laboratory instruments. Due to their long focal lengths, these instruments demand stringent environmental conditions (temperature, humidity, vibration) for stability. As they typically employ dispersive systems with silicon-based detectors, the common excitation

wavelengths are in the ultraviolet and visible regions. High-energy UV light can damage biological samples, so visible light excitation is commonly used, resulting in higher fluorescence backgrounds that have driven the development of fluorescence background removal algorithms.

2.2 Fourier Transform Raman Spectroscopy

Raman signals are susceptible to interference from chromophore fluorescence. Fourier transform Raman spectroscopy, first practically applied by Hirschfeld and Chase in 1986, combines near-infrared excitation with Fourier transform technology [8]. Without grating dispersion, this technique generally achieves higher signal-to-noise ratios than dispersive spectrometers under equivalent parameters. Using 1064 nm laser excitation, it significantly reduces sample fluorescence and avoids fluorescence interference while enhancing Raman signal intensity and signal-to-noise ratio [9]. Researchers have summarized its potential for food analysis [10], and recent work has explored combining visible lasers with Fourier transform spectrometers [11], representing a promising new trend.

2.3 Surface-Enhanced Raman Spectroscopy (SERS)

The surface-enhanced Raman effect was first discovered by Fleischmann et al. in 1974 [12], catalyzing research on enhanced Raman spectroscopy. SERS addresses the low sensitivity of spontaneous Raman spectroscopy. When target molecules adsorb onto rough metal surfaces, their Raman signals are effectively enhanced through physical and chemical enhancement mechanisms [13]. SERS-active substrate preparation is essential, with only a few metals (gold, silver, copper) exhibiting strong SERS effects. Nanotechnology advances have greatly improved substrate preparation methods.

Different substrates produce varying enhancement effects, requiring tailored development for specific analytes to improve detection sensitivity and stability. For trace substances, substrates with enrichment-functional materials are needed; for analytes with weak metal affinity, modifications with aptamers or other substances enable affinity enrichment. SERS has been applied to plant hormone analysis and plant pathogen detection [14]. The technique offers 3-4 orders of magnitude signal enhancement, providing high sensitivity and low detection limits. However, traditional SERS suffers from low stability, particularly for quantitative analysis, and photothermal effects can damage biomolecules, limiting biocompatibility. Improving qualitative and quantitative stability represents the next development direction.

2.4 Tip-Enhanced Raman Spectroscopy (TERS)

Conventional micro-Raman spectroscopy is limited by optical diffraction and detector sensitivity for nanoscale characterization. TERS combines scanning probe microscopy with SERS, offering high sensitivity and nanoscale spatial resolution [15]. When incident light illuminates a sharp metal probe tip, localized

surface plasmon resonance, lightning rod, and antenna effects generate intense localized electromagnetic field enhancement within a few to tens of nanometers, enhancing Raman signals from samples beneath the tip [16]. Scanning the probe enables simultaneous topographical characterization and nanoscale localized Raman spectroscopy.

TERS has been applied to RNA sequence detection [17], pesticide analysis [18], and bacteria/virus detection [19,20]. Its advantage lies in providing higher spatial resolution, even reaching nanoscale, enabling molecular-level research and opening new possibilities for nanoscale chemical analysis and imaging. However, measuring stable results requires TERS probes with consistent dimensions, precisely controlled optical properties, long-term stability, and reusability—requirements not yet fully met by current technology.

2.5 Resonance Raman Spectroscopy

Resonance Raman spectroscopy adjusts excitation energy near the electronic transition energy of the target molecule to achieve resonance enhancement. However, resonance excitation wavelengths typically fall in the UV-visible region, making this method susceptible to fluorescence interference [21-23]. Its advantage is high sensitivity; compared to spontaneous Raman, signal intensity can be enhanced by 2-6 orders of magnitude [24,25]. Since excitation light can induce electronic transitions, the obtained spectra often have strong fluorescence backgrounds. Pre-resonant excitation wavelengths can reduce fluorescence, but the reduction is limited.

Resonance Raman spectroscopy has been successfully applied to plant pigment detection, such as carotenoids, where 532, 514.4, and 488 nm lasers in the visible region produce resonance enhancement effects [24,25].

2.6 Spatially Offset Raman Spectroscopy (SORS)

SORS collects Raman signals at a spatial offset from the illumination point on the sample surface. Larger offsets yield greater contributions from deeper sample layers. Conventional backscattering Raman spectroscopy has shallow penetration depth, only obtaining surface composition, while transmission Raman spectroscopy cannot reflect information at different depths. SORS enables non-destructive detection of internal chemical information.

SORS has been applied to salmon quality assessment [26] and non-invasive evaluation of potato tuber nutrients [27]. Its advantage is obtaining internal composition information without damaging the sample surface, enabling depth-resolved compositional analysis. However, for samples with strong excitation light absorption, Raman signal intensity decreases. Compared to conventional Raman, SORS requires higher quantum efficiency CCDs and complex optical designs, increasing costs [28].

2.7 Shifted Excitation Raman Difference Spectroscopy

Based on the principle that Raman shift is independent of excitation wavelength, this technique uses two similar excitation wavelengths to obtain spectra for differential analysis, effectively reducing fluorescence background and analyzing weak Raman signals [29]. It has been applied to soil component detection [30]. The unique algorithmic and optical advantages improve signal-to-noise ratio, but require dual-wavelength excitation with complex optical designs, sometimes needing dual optical paths, increasing system complexity.

2.8 Nonlinear Optics-Based Raman Spectroscopy

Two Raman techniques based on nonlinear optics are coherent anti-Stokes Raman spectroscopy (CARS) [31] and stimulated Raman spectroscopy (SRS) [32]. Currently focused on rapid imaging, these techniques have limited agricultural applications. SRS has been used for imaging plant cuticular waxes and xylan [33], while CARS has been applied to lignin imaging in plant cell walls [34]. SRS enhances Raman scattering cross-section through two-photon resonance, significantly improving signal-to-noise ratio. CARS studies anti-Stokes scattering, avoiding fluorescence interference. Both enable fast spectral imaging but require more complex optical configurations, sometimes including femtosecond lasers, making them expensive.

The advantages and disadvantages of these techniques are compared in .

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3 Applications of Raman Spectroscopy in Agricultural Detection

Raman spectroscopy applications in agriculture primarily include plant detection, soil analysis, water quality monitoring, and food safety assessment.

3.1 Plant Detection

Raman spectroscopy's "molecular fingerprint" capability enables specific identification of biomolecules without sample preparation, meeting the need for in vivo identification and characterization of specific molecules and their concentrations in plants.

3.1.1 Plant Phenotyping Research Raman spectroscopy can assess fruit maturity, providing guidance for timely harvest to improve economic benefits. Khodabakhshian et al. [35] analyzed pomegranates at four maturity stages (88-143 days post-flowering) using Fourier transform Raman spectroscopy. Unsupervised principal component analysis (PCA) distinguished four pomegranate types, while supervised partial least squares discriminant analysis (PLS-DA) and soft independent modeling of class analogy (SIMCA) achieved 96% and

95% accuracy for training and validation sets, respectively. Binary classification (“ripe” vs. “unripe”) using PCA-SIMCA reached 100% accuracy. Qin et al. [36] explored SORS for non-destructive tomato internal maturity evaluation, separating exocarp and Teflon layer signals through fluorescence-corrected spectral modeling to detect internal carotenoid changes.

Raman spectroscopy combined with chemometrics can classify plant varieties. Morey et al. [37] standardized potato spectra to the 1460 cm^{-1} peak and used SORS to analyze nutritional components, achieving variety identification and origin determination. Farber et al. [38] used orthogonal partial least squares and seed Raman spectroscopy for peanut genotype discrimination with 95% accuracy, demonstrating that Raman spectroscopy can identify peanut varieties based on leaf and seed spectral features for precision breeding. Jentzsch et al. [39] distinguished Ecuadorian cocoa bean varieties with 91.8% accuracy using chemometric analysis of spectral data. Krimmer et al. [40] rapidly typed six maize varieties and assessed their nutrient content using a handheld Raman spectrometer.

Raman spectroscopy characterizes biomacromolecules in plants. Zhang et al. [41] detected plant hormone abscisic acid using SERS with a 0.1 µmol/L detection limit, showing good agreement with ELISA. Carotenoids have been extensively studied; Schulz et al. [42] demonstrated the unique advantages of near-IR FT-Raman for in situ carotenoid research. Raman spectroscopy enables imaging of cell wall polysaccharides (cellulose, hemicellulose, pectin) at cellular and multicellular levels to study fruit softening mechanisms during post-harvest storage [43]. Lignin research using Raman spectroscopy has also been explored [44,45], with Oliveira et al. [46] characterizing plant cell walls to identify varieties with lower lignin content and higher saccharification efficiency.

3.1.2 Plant Stress Detection Plant stress includes abiotic (light, water, salt, temperature) and biotic (diseases, pests) factors. Early stress identification enables timely management interventions to improve yield.

Raman spectroscopy monitors abiotic stress. Huang et al. [47] monitored nitrogen status in Arabidopsis, bok choy, and flowering cabbage, identifying the 1046 cm^{-1} peak for nitrogen state characterization and enabling early nitrogen deficiency diagnosis before visible symptoms. Sanchez et al. [48] used portable Raman spectroscopy to diagnose nitrogen, phosphorus, and potassium deficiencies in rice and pre-diagnose moderate to high salt stress. Gupta et al. [49] demonstrated that portable leaf-clip sensors can detect nitrogen deficiency and drought stress, with results consistent with laboratory benchtop instruments. Zhao et al. [50] used confocal Raman spectroscopy to scan healthy, early zinc-deficient, and zinc-deficient rice leaves, finding that zinc deficiency increased carotenoid content while decreasing starch, protein, sugars, and amino acids, achieving 100% discrimination using least squares support vector machine modeling.

For biotic stress, Sanchez et al. [51] observed spectral changes from cowpea weevil larvae and excrement, showing that chemometrics combined with Raman spectroscopy could accurately distinguish infested from uninfested seeds. The team also achieved 80% accuracy for non-invasive diagnosis of Liberibacter disease in tomatoes using portable Raman spectroscopy [52]. In plant pathogen diagnostics, Sanchez et al. [53] validated Raman spectroscopy against qPCR for citrus Huanglongbing (HLB) detection, finding Raman spectroscopy more sensitive and capable of detecting HLB-specific spectral features in qPCR-negative plants. Lin et al. [54] detected banana fusarium wilt using SERS with 76.2% detection rate for asymptomatic samples, comparable to RT-PCR. Dai et al. [55] used Raman and autofluorescence spectroscopy to differentiate healthy citrus samples from HLB-infected samples with 94.75% accuracy using PLS-DA models.

Raman spectroscopy also studies heavy metal and nanoparticle pollution stress. Timchenko et al. [56] investigated copper ion concentration effects on plant optical properties using Raman spectroscopy.

3.1.3 Summary Raman spectroscopy for plant phenotyping and stress detection has gained widespread attention. Dedicated Raman sensors enable convenient field data acquisition for big data analytics. However, research combining Raman spectroscopy with chemometrics and machine learning algorithms requires further strengthening to improve accuracy in plant origin classification, maturity assessment, and other applications.

3.2 Soil Detection

Raman spectroscopy applications in soil include pesticide residue detection, microbial community analysis, and nutrient assessment.

3.2.1 Soil Pesticide Residue Detection Zhang et al. [57] first proposed SERS detection of thiram in soil, but required centrifugal extraction and additives for adsorption onto nanoparticles. For on-site measurement in complex matrices, Lin et al. [58] developed a paper-based SERS substrate achieving a 0.56$×10^{5}$ enhancement factor with 12.8% point-to-point intensity variation, enabling quantitative thiram detection without pretreatment. Raman spectroscopy effectively detects various pesticides including thiabendazole, prometryn, and atrazine [59,60].

3.2.2 Soil Microbial Detection Biological nitrogen fixation converts inert N_2 to bioavailable nitrogen. Li et al. [61] used D_2O-labeled single-cell Raman spectroscopy to detect phosphate-solubilizing bacteria in soil, using C-D band intensity ratios as a semi-quantitative biological indicator of phosphorus release. Schwarz et al. [62] developed a polyethyleneimine-modified particle strategy to isolate various bacteria from soil, achieving 92% identification accuracy using Raman spectroscopy with chemometrics.

3.2.3 Soil Nutrient Detection Rapid determination of water-soluble nitrogen in soil aids scientific fertilization. Dong et al. [63] used SERS with Opto Trace Raman 202 substrate for quantitative water-soluble nitrogen detection, achieving high prediction accuracy ($Rp^2 = 0.91$, RMSEp = 8.76 mg/L, RPD = 3.00). Characteristic peaks at 1028, 1370, 1436, and 1636 cm^{-1} were identified, with the 1370 cm^{-1} peak showing the strongest correlation (Rp = 0.94). PCA and LS-SVM achieved 86.67% classification accuracy for high vs. low nitrogen content soils. Phosphorus detection using visible Raman microscopy was initially hindered by fluorescence from soil organics, but deep UV excitation later avoided this interference [64,65].

3.2.4 Summary Raman spectroscopy detects biological and non-biological soil components, enabling trace detection of pesticide residues, microbes, and nutrients. However, detection is complex, generally requiring SERS enhancement. The poor quantitative performance of SERS substrates challenges reliability, necessitating development of more stable substrates for soil research.

3.3 Water Quality Detection

Raman spectroscopy detects water pollutants including organics, inorganics, and biological contaminants.

For heavy metals and chemical pollutants, Liu et al. [66] combined manganese co-precipitation with Raman spectroscopy, achieving prediction correlation coefficients of 0.979, 0.964, 0.956, and 0.972 for copper, zinc, cadmium, and lead, respectively. Hu et al. [67] developed a metal-organic framework SERS substrate embedding gold nanoparticles in MIL-101 for p-phenylenediamine detection in environmental water ($R^2 = 0.995$ for 1-100 ng/mL). Mariño-López et al. [68] used microporous silica capsules containing gold nanoparticles as molecular sieves to prevent biofouling, achieving 1.77 g/L detection limit for DDT.

For pesticide residues in water, direct SERS detection suffers from non-specific co-adsorption. The microporous SERS substrate approach enables specific detection of contaminants like DDT [68].

Raman spectroscopy also detects waterborne pathogens. Escoriza et al. [69] evaluated Raman spectroscopy for quantifying filtered waterborne bacteria, showing good correlation with turbidity ($R^2 = 0.92$), plate counting ($R^2 = 0.87$), and dry weight ($R^2 = 0.97$). Yang et al. [70] studied water hardness using Raman spectroscopy, finding that the bending-to-stretching vibration intensity ratio decreases with total hardness, providing a simple water quality analysis method. Li et al. [71,72] comprehensively reviewed Raman spectroscopy for water quality monitoring, summarizing advantages and limitations for various pollutant types. Raman spectroscopy also enables water temperature detection [73,74].

Since water is a transparent matrix with weak Raman scattering, direct detection of aqueous molecules is feasible. However, low concentrations and complex

compositions require concentration and specific treatment methods to achieve higher sensitivity and accuracy.

3.4 Food Detection

Raman spectroscopy applications in food safety focus on pesticide residue detection, adulteration identification, and quality assessment.

3.4.1 Food Pesticide Residue Detection Pesticide residues on fruits and vegetables pose serious health risks. Kong et al. [75] used polyethylene glycol-modified gold nanoparticle sol to detect thiram residues on produce surfaces, achieving detection limits of 4.62, 7.83, and 10.74 g/L for apples, pears, and vegetables—well below the 5 g/mL national standard. Hu et al. [76] developed a non-destructive method using SERS with self-assembled gold nanorod arrays and self-modeling mixture analysis (SMA) for simultaneous detection of thiram and thiabendazole mixtures on fruit surfaces, achieving detection limits of 0.029-0.047 ng/cm^2 for thiram and 0.76-0.80 ng/cm^2 for thiabendazole. Dhakal et al. [77] identified the 677 cm^{-1} Raman peak as a chlorpyrifis fingerprint, establishing a multiple linear regression model with correlation coefficients of 0.86 and 0.81 for calibration and validation. Zhang et al. [78] detected imazalil residues in navel orange flesh using SERS with PCA and support vector regression (Rp = 0.9156). Tsagkaris et al. [79] reviewed optical screening methods for pesticide residues, including spontaneous and surface-enhanced Raman spectroscopy.

3.4.2 Food Adulteration Detection Economic incentives drive food adulteration. Joshi et al. [82] used 1295 cm^{-1} Raman imaging for non-invasive analysis of fake eggs, enabling discrimination between real and counterfeit products. Oroian et al. [83] studied honey adulterated with various sugars, achieving 96.54% accuracy for authentic vs. adulterated honey identification using PLS-DA. Xu et al. [84] reviewed Raman spectroscopy with chemometrics for food authentication.

3.4.3 Food Quality Assessment Raman spectroscopy evaluates food quality. Ahmad et al. [85] studied temperature effects on desi ghee composition, identifying safe cooking temperatures (140-180 °C) where molecular composition remains unchanged. Velioğlu et al. [86] differentiated fresh vs. frozen-thawed fish samples using Raman spectroscopy with chemometric analysis. Fowler et al. [87] predicted lamb semimembranosus tenderness using Raman spectroscopy, which may be superior to particle size analysis for assessing shear force variations.

3.4.4 Summary Simple sample preparation makes Raman spectroscopy ideal for rapid detection of drug residues, adulteration, and quality assessment, enabling large-scale food safety screening.

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4 Challenges and Future Prospects

This paper summarizes typical Raman spectroscopy techniques, their principles, advantages, disadvantages, and applications in plant, soil, food, and water quality detection. As a molecular spectroscopy technique, Raman spectroscopy has achieved fruitful results in agricultural applications due to its rapid and in vivo measurement capabilities. However, as a relatively new technology in agriculture, several specific challenges remain.

4.1 Problems to be Addressed

Fluorescence Interference: Many agricultural samples, particularly biological materials, generate strong fluorescence under visible excitation that can overwhelm Raman signals. Solutions include: (1) System improvements: near-IR excitation (e.g., 1064 nm with InGaAs detectors) effectively reduces fluorescence [88]; shifted excitation Raman difference spectroscopy also eliminates fluorescence [89]. (2) Algorithmic approaches: airPLS [90] and polynomial fitting algorithms perform baseline correction. Developing specialized Raman instruments optimized for agricultural matrices (soil, water, plants, animals) is a key direction.

Sensitivity Requirements: Agricultural applications demand high sensitivity for target identification and analysis. SERS is promising for ultra-trace detection but suffers from signal fluctuations that limit quantitative reliability. Improved SERS substrates with specific modifications for different analytes can enhance stability, sensitivity, and reusability while improving biocompatibility [91]. Fourier transform Raman spectroscopy provides stronger signals than dispersive systems [88], and resonance Raman spectroscopy effectively enhances sensitivity.

Imaging Speed: Spectral imaging is a powerful tool for studying spatial distribution of chemical components, but current Raman imaging speeds cannot achieve real-time analysis. Faster imaging techniques like SRS and CARS have been applied to plant studies [33,34], but their complex optical configurations and high costs limit widespread adoption.

4.2 Future Research Directions

Plant Science: Raman spectroscopy' s water insensitivity makes it ideal for in vivo plant measurements. Its "molecular fingerprint" capability enables characterization of various plant substances, supporting field-based phenotyping sensor development. Future research will focus on plant phenotyping using dedicated Raman sensors for rapid field data acquisition.

Animal Science: Combining Raman spectroscopy with chemometrics can monitor physiological-chemical conditions in live animals to infer health status. Current monitoring is limited to few indicators like glucose [92]; more research is needed for comprehensive physiological monitoring.

Instrumentation: Agricultural detection scenarios require diverse measurement modalities. Portable Raman spectrometers enable in situ plant measurements, but more stable and accurate portable methods need development. Remote Raman spectroscopy has been studied for water temperature [73,74] but not yet for other agricultural applications. Future integration of active Raman sensors on drones and agricultural machinery could enable ground and near-ground coordinated information acquisition.

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