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Applications and Countermeasures of Rapid Soil Pollution Detection Technologies in Agricultural Production

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Abstract: As agricultural intensification and industrialization continue to accelerate in China, soil pollution in farmland has become increasingly prominent, posing serious threats to food safety and ecosystem health due to heavy metals, organic pollutants, and microplastics. Although traditional laboratory detection methods feature high accuracy, they suffer from limitations including prolonged detection duration, high costs, and complex operational procedures, rendering them incapable of meeting the demand for real-time, rapid assessment of soil quality in modern agriculture. In this paper, the research progress of rapid detection technology of soil pollution in recent years is systematically reviewed, and the principle and characteristics of mainstream technologies such as visible near infrared spectroscopy, portable X-ray fluorescence spectroscopy, and laser-induced breakdown spectroscopy are analyzed. On this basis, the application value of these technologies in farmland heavy metal screening, sampling optimization, nutrient detection and contaminated site investigation was discussed, the limitations of current technologies were analyzed, and the future development strategy of rapid detection technology was put forward, in order to provide technical support for the prevention and control of agricultural soil pollution and sustainable development.

Keywords: Soil pollution; rapid detection technology; agricultural production; application countermeasures and suggestions.

1. Introduction

As the fundamental support for human survival and sustainable development, soil constitutes the basic foundation of agricultural systems. Soil supports plant growth and material decomposition processes, and is an important part of the material cycle[2]. Soil quality is directly related to food security, agricultural product quality, and ecological balance. However, in recent years, with the emission of industrial "waste", excessive input of agricultural chemicals, spread of traffic pollution, and the acceleration of urbanization, agricultural soil pollution issues in China have become increasingly prominent. Heavy metals, organic pollutants, and microplastics pose multiple threats to the soil environment. Acting via the enrichment effect of the food web, these pollutants critically endanger human health while simultaneously reducing soil quality and suppressing agricultural crop performance[1-4].

At present, China's approach to pollutant detection is still dominated by conventional laboratory-based analytical techniques, including atomic absorption spectrometry (AAS) and inductively coupled plasma mass spectrometry (ICP-MS), among others. However, despite their high accuracy, low detection limits, and reliable precision, traditional laboratory detection methods have significant limitations, such as long cycles, high costs, and complex operations, making them difficult to meet the on-site, real-time, and high-throughput detection needs of modern agriculture. Therefore, the development of rapid detection technologies for soil pollution suitable for agricultural production has become an important research and development direction in the fields of environmental monitoring and agricultural science and technology [5-6]. Rapid detection technology can directly obtain soil pollution information in the field, significantly shorten the detection cycle, reduce the detection cost, and provide decision-making basis for timely taking pollution prevention and control measures[4,7].

Based on the research results at home and abroad in recent years, this paper systematically reviewed the application progress of soil pollution rapid detection technology in agricultural production, analyzed the characteristics and applicability of various technologies, and proposed the research direction and development strategy of soil pollution rapid detection technology in the future.

2. Main Rapid Detection Technologies and Their Principle Characteristics

2.1. Spectroscopic Detection Techniques

As an analytical method, spectroscopy is founded on how matter interacts with light to reveal its composition and structure. The electromagnetic spectrum is typically divided into ultraviolet, visible, and infrared regions according to wavelength. Upon illumination, atoms, molecules, and ions within a material absorb light at specific wavelengths, which causes them to undergo energy level transitions. At the same time, due to the differences in atomic structure, molecular structure, and chemical bonding of different substances, the wavelengths and intensities of the absorbed light are also different, thus forming characteristic spectra of the substances[8].

2.1.1. Portable X-ray Fluorescence Spectrometry (PXRF)

Portable X-ray Fluorescence Spectrometry (PXRF) is a field rapid detection technology based on the principle of X-ray fluorescence analysis. Its basic principle is that the built-in X-ray tube of the instrument emits high-energy X-rays to irradiate soil samples, which excites the transition of electrons in the inner layer of atoms in the samples. When the outer layer electrons fill the inner hole, they release secondary X-ray fluorescence with characteristic energy. Different elements produce different fluorescent energy. The type of elements can be identified by measuring the fluorescence spectrum with a detector, and the fluorescence intensity is proportional to the content of elements, so as to realize quantitative analysis[6,9].

PXRF is an analytical method for simultaneous determination of multiple elements. This technology has the advantages of simple spectral line, less interference, fast analysis speed, simple sample preparation, good reproducibility, simultaneous determination of multiple elements and nondestructive and rapid detection on site. At present, PXRF technology can basically meet the rapid detection of arsenic, lead, copper, zinc, chromium, calcium, iron and other heavy metals and trace elements in general farmland soil, but it can not accurately determine cadmium, mercury, nickel, selenium, antimony and other elements in farmland soil. The detection ability of nitrogen, phosphorus and potassium is weak; the detection limit is relatively high, and the detection accuracy of trace pollutants is insufficient; the test results are greatly affected by matrix effects such as soil moisture, organic matter content and particle size[6,9].

2.1.2. Visible-Near Infrared Reflectance Spectroscopy (Vis-NIR)

Vis-NIR technology mainly reflects the soil attribute information through the frequency doubling and harmonic of the fundamental frequency information of the characteristic functional groups in the infrared spectrum region. It has the characteristics of fast analysis speed, simple sample preparation, low cost, non-destructive determination and multi-attribute simultaneous prediction. Some studies have pointed out that soil moisture has obvious absorption characteristics at 1400 and 1900 nm, and there is a good quantitative relationship between soil reflectance and water content in the whole spectral region; Iron also has obvious spectral characteristics in the visible light range; Clay minerals and calcium carbonate have weak spectral characteristics in the near infrared region. Heavy metals in soil have no obvious spectral characteristics in the Vis-NIR spectral region, but the detection of heavy metals can be indirectly realized based on the relationship between heavy metals and organic matter and iron in soil. Further calibration of different regions during detection can usually obtain better prediction accuracy[6].

2.1.3. Laser-induced breakdown spectroscopy (LIBS)

The principle of LIBS technology is to focus high-energy laser pulses on the surface of soil samples, make the samples instantly gasified into high-temperature, high-density plasma, and measure the wavelength and intensity of spectral lines in the plasma atomic emission spectrum, so as to obtain the composition and content of elements in soil samples. This technology can be used for analysis and testing under non-destructive or non-contact conditions, without sample pretreatment or simple pretreatment. It is convenient and rapid for analysis, and can carry out multi-parameter analysis of soil samples at the same time. It can carry out continuous measurement on site, and truly realize the rapid detection of soil multi parameters. The detection accuracy is greatly affected by the soil matrix effect, and the equipment cost is high[5,6].

2.1.4. Arc Emission Spectroscopy (AES)

AES technology uses an arc light source to provide energy for sample atomization and excitation. Based on atomic emission spectrometry technology, according to the atoms or ions of each chemical element under thermal or electrical excitation, the outer electrons transition from high energy level to low energy level, and the energy is emitted in the form of electromagnetic radiation, so as to generate a spectrum for qualitative, semi quantitative and quantitative analysis of elements. AES technology can detect multiple elements at the same time, with fast analysis speed, good selectivity and low detection limit[6].

2.1.5. Other Spectroscopic Techniques

Differential Optical Absorption Spectroscopy (DOAS) and terahertz spectroscopy are new rapid detection technologies. The former is based on the narrow-band absorption characteristics of molecules to UV-Vis light. Combined with the deep learning algorithm, it can realize the high-precision identification of heavy metals and organic pollutants. It has the advantages of good selectivity, high sensitivity and fast detection speed, but it is easily disturbed by environmental factors and has strong algorithm dependence; The latter uses the fingerprint spectral characteristics of terahertz band substances to show unique recognition ability for typical pollutants such as microplastics and hexavalent chromium. It has the characteristics of strong penetration, high safety and good specificity, but it is extremely sensitive to water molecules. The sample needs to be fully dried, and the equipment cost is high[10].

2.2. Electrochemical Sensing Technology

Electrochemical sensors work according to ionic conductivity, and are often used to detect and measure the concentration of substances. The electrode of the sensor reacts with the target analyte to cause charge transfer, which changes the current or potential and generates signals. After that, the signal is converted into a measurable electrical signal by the converter in the conversion system. Because the electrical signal is proportional to the concentration of the target substance, the target component can be analyzed qualitatively or quantitatively. Classification of electrochemical sensors by reaction mechanism yields three types, namely potentiometric, conductometric, and amperometric sensors[11].

2.3. Gamma Spectrometry

Gamma ray spectrometry is a passive non-destructive testing technology based on the characteristic gamma ray released by the decay of natural radionuclides in soil. Its basic principle is to passively receive the gamma ray emitted by the soil through the scintillation detector or semiconductor detector placed about 0.6 meters above the soil. After obtaining the energy spectrum, the nuclide type is identified by the characteristic peak energy, and the nuclide content is calculated by the peak area. The parameters such as soil nutrient, texture, organic matter and so on are retrieved by using the significant correlation between the radionuclide content and soil physical and chemical properties[12].

3. Current Application Status in Agricultural Production

3.1. Screening and sampling optimization of heavy metal pollution in farmland soil

PXRF and LIBS technologies can realize the on-site quantitative detection of heavy metals in soil, and effectively identify the contaminated areas and risk levels. Some studies have pointed out that the detection model based on machine learning has high accuracy and stability in the prediction of heavy metal content, and the prediction accuracy is better than the traditional linear regression method. The combination of rapid detection results and spatial interpolation technology can optimize the sampling strategy, significantly reduce the number of laboratory samples, and reduce the detection cost under the premise of ensuring the prediction accuracy [5−6,9,13].

3.2. Rapid detection of soil nutrients and precision fertilization

Vis-NIR technology combined with chemometrics models can rapidly predict soil organic matter, total nitrogen, available phosphorus, available potassium and other indicators. Aiming at the problem of insufficient generalization ability among different soil types, the transfer correction method can effectively improve the prediction accuracy of the model in different regions. The gamma ray spectrum method realizes the digital mapping of soil nutrients in large-scale farmland, and provides basic data support for precision fertilization. The soil nutrient prescription map generated based on the rapid detection results can guide variable rate fertilization, realize the uniform management of soil nutrients, and reduce the amount of chemical fertilizer [6,12].

3.3. Detection of Typical Pollutants

Terahertz spectroscopy technology has good recognition ability for typical pollutants such as microplastics and hexavalent chromium. Qualitative and quantitative detection can be realized by analyzing the changes of absorption coefficient and refractive index. DOAS technology also shows high precision and recall in the detection of organic pollutants[10].

3.4. Application of Polluted Site Investigation

In the investigation of contaminated sites, the integrated application of a variety of rapid detection technologies is often required. At the stage of preliminary site investigation, PXRF or LIBS can be used for rapid screening to identify pollution hotspots and boundaries; In the detailed investigation stage, the key points can be accurately quantified in combination with laboratory analysis methods; In the assessment stage of remediation effect, rapid detection technology can be used to track and monitor the restored soil[9].

3.5. Application in Remediation Effect Evaluation and Long-term Monitoring

The rapid detection technology can also be used for tracking and monitoring of soil remediation projects and long-term dynamic management of farmland soil quality. In the evaluation of remediation effect, pxrf is used to quickly compare and detect the soil before and after remediation, which can quickly evaluate the remediation effect and guide the adjustment and optimization of remediation scheme. In terms of long-term monitoring, electrochemical sensors can be buried in farmland to realize soil salinity and pH monitoring. The monitoring data can be transmitted to the cloud platform in real time through the Internet of things to provide technical support for the dynamic management of soil quality.

4. Analysis of Technical Limitations

The trade-off between detection accuracy and stability is a primary concern. On-site rapid detection technology has advantages in detection speed and portability, but due to factors such as soil matrix effects, moisture content, and particle size, its detection accuracy and repeatability are often lower than laboratory methods.

The insufficient generalization ability of models is also a limiting factor. Technologies such as Vis-NIR and LIBS are highly dependent on calibration models, and their generalization ability is limited under different soil types, climatic conditions, and farming practices. When applied across regions, it often requires re-modeling or transfer calibration, which increases the difficulty of promotion.

Currently, most rapid detection devices primarily rely on a single or a limited number of parameters, making it difficult to meet the practical needs of simultaneously detecting multiple indicators such as heavy metals, nutrients, organic pollutants, salinity, and pH in agricultural production.

The detection technology for typical pollutants is not yet mature. Technologies such as terahertz spectroscopy and DOAS have shown potential for detecting typical pollutants such as microplastics and hexavalent chromium, but issues such as high equipment costs, complex operation, and significant interference from environmental factors have not yet been fully resolved.

5. Development Suggestions

Portable detection terminals integrating multiple principles should be developed to achieve simultaneous and rapid detection of indicators such as heavy metals, nutrients, and organic pollutants, meeting the comprehensive monitoring needs of agricultural production.

The integration of artificial intelligence and Internet of Things technologies will drive technological upgrading. By establishing a spectral inversion model based on deep learning and combining IoT and GIS technologies, an integrated smart soil monitoring system can be constructed to achieve real-time early warning and intelligent decision-making for soil pollution.

Technical standardization and promotion and application urgently need to be advanced. It is necessary to accelerate the formulation of national or industry standards for rapid soil testing technology and unify the normative requirements for data collection, model construction, result expression, and other aspects.

Combining rapid detection equipment with drones, intelligent tractors, and other equipment enables synchronous soil data collection, real-time prescription map generation, and variable fertilization guidance during the cultivation process, truly achieving an integrated "measurement-control-application" precision agriculture.

6. Conclusion

Rapid detection technology for soil pollution is rapidly developing toward on-site intelligence and multi-parameterization. In the future, efforts should be made to strengthen the integration of multiple principles, artificial intelligence fusion, standardization promotion, and collaborative development with intelligent agricultural machinery, promoting the widespread application of rapid detection technology in agricultural production and providing technical support for China's green agricultural development and food security.

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