Nanotechnology-based sensors for real-time monitoring and assessment of soil health and quality: A Review

Abstract:

Soil health and quality are critical factors in maintaining sustainable agriculture, ecosystem stability, and global food security. Conventional methods for assessing soil properties are often time-consuming, labor-intensive, and lack real-time monitoring capabilities. Nanotechnology has emerged as a promising approach to develop advanced sensors for rapid, in-situ, and continuous monitoring of soil health parameters. This comprehensive review discusses the recent advancements in nanotechnology-based sensors for soil health assessment, their working principles, applications, challenges, and future prospects. We highlight the potential of various nanomaterials, such as carbon nanotubes, graphene, metal oxide nanoparticles, and quantum dots, in fabricating highly sensitive, selective, and robust soil sensors. The integration of these nanosensors with wireless communication technologies and data analytics enables real-time monitoring and precision agriculture practices. Furthermore, we discuss the environmental and ecological implications of deploying nanosensors in soil and the need for standardized protocols and regulations. This review provides valuable insights into the current state-of-the-art and future directions of nanotechnology-based sensors for soil health monitoring, promoting sustainable agriculture and environmental management.

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Keywords: Nanotechnology, soil sensors, soil health, precision agriculture, sustainable agriculture

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1. Introduction

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1.1 Importance of soil health and quality Soil is a vital natural resource that supports plant growth, nutrient cycling, water regulation, and biodiversity [1]. Healthy soil is essential for sustainable agriculture, ensuring food security, and maintaining ecosystem services [2]. Soil health refers to the capacity of soil to function as a living system, sustaining plant and animal productivity, maintaining water and air quality, and promoting plant and animal health [3]. Soil quality, on the other hand, is the ability of soil to perform specific functions, such as nutrient retention, water infiltration, and carbon sequestration [4]. Assessing and monitoring soil health and quality are crucial for making informed decisions in agricultural management, environmental protection, and land-use planning [5].

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1.2 Limitations of conventional soil assessment methods Conventional methods for assessing soil health and quality rely on laboratory analysis of soil samples, which is time-consuming, labor-intensive, and provides only a snapshot of soil conditions at a particular time and location [6]. These methods often require sophisticated instruments, skilled personnel, and are destructive to soil samples [7]. Moreover, the spatial and temporal variability of soil properties makes it challenging to obtain representative samples and monitor soil health in real-time [8]. These limitations highlight the need for advanced technologies that can provide rapid, in-situ, and continuous monitoring of soil health parameters.

1.3 Nanotechnology-based sensors for soil health monitoring Nanotechnology has emerged as a promising approach to develop advanced sensors for various applications, including environmental monitoring, healthcare, and agriculture [9]. Nanotechnology involves the manipulation of matter at the nanoscale (1-100 nm), where materials exhibit unique physical, chemical, and biological properties [10]. These properties can be exploited to fabricate highly sensitive, selective, and miniaturized sensors for detecting and quantifying soil health parameters [11]. Nanotechnology-based sensors offer several advantages over conventional methods, such as real-time monitoring, high spatial resolution, low power consumption, and the ability to integrate with wireless communication technologies [12].

2. Working principles of nanotechnology-based sensors

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1.1 Carbon nanotubes (CNTs) Carbon nanotubes (CNTs) are cylindrical nanostructures composed of rolled-up graphene sheets, with diameters ranging from 0.4 to 100 nm and lengths up to several micrometers [13]. CNTs exhibit exceptional mechanical, electrical, and thermal properties, making them suitable for sensing applications [14]. CNT-based sensors rely on the changes in electrical conductivity or resistance when the nanotubes interact with target analytes [15]. The high surface-to-volume ratio and unique electronic structure of CNTs enable highly sensitive and selective detection of various soil health parameters, such as nutrients, heavy metals, and organic contaminants [16].

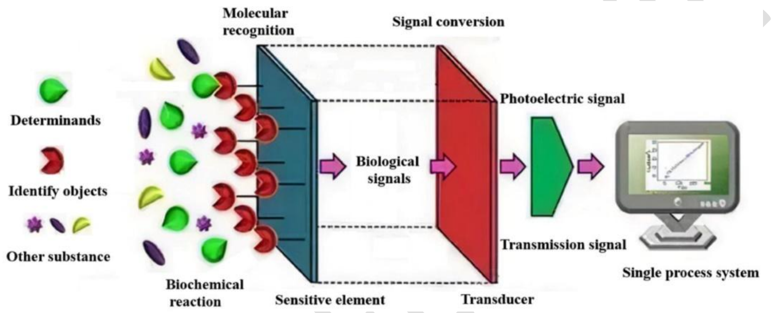

Figure 1: Schematic representation of a carbon nanotube-based sensor for soil health monitoring.

1.2 Graphene Graphene is a two-dimensional nanomaterial consisting of a single layer of carbon atoms arranged in a hexagonal lattice [17]. Graphene exhibits exceptional electrical, mechanical, and optical properties, making it an attractive material for sensing applications [18]. Graphene-based sensors exploit the changes in electrical conductivity, resistivity, or capacitance when graphene interacts with target analytes [19]. The high surface area, electron mobility, and low noise characteristics of graphene enable highly sensitive and selective detection of soil health parameters [20].

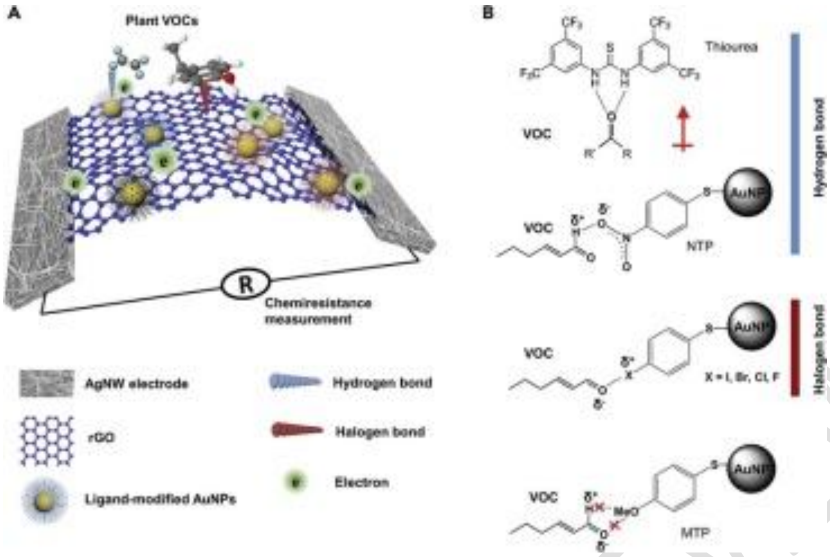

Figure 2: **Schematic representation of a graphene-based sensor for soil health monitoring.**

2.3 Metal oxide nanoparticles Metal oxide nanoparticles, such as zinc oxide (ZnO), tin oxide (SnO2), and titanium dioxide (TiO2), have been widely used in sensing applications due to their unique electrical, optical, and catalytic properties [21]. Metal oxide nanoparticle-based sensors rely on the changes in electrical conductivity or resistance when the nanoparticles interact with target analytes [22]. The high surface-to-volume ratio, chemical stability, and tunable bandgap of metal oxide nanoparticles enable sensitive and selective detection of soil health parameters, such as pH, moisture, and gas emissions [23].Figure 3: Schematic representation of a metal oxide nanoparticle-based sensor for soil health monitoring.

2.4 Quantum dots (QDs) Quantum dots (QDs) are semiconductor nanocrystals with sizes ranging from 2 to 10 nm [24]. QDs exhibit unique optical and electronic properties, such as size-dependent emission wavelength, broad absorption spectra, and high quantum yield [25]. QD-based sensors exploit the changes in fluorescence or photoluminescence when the QDs interact with target analytes [26]. The tunable emission wavelength, photostability, and high sensitivity of QDs enable multiplexed detection of soil health parameters, such as heavy metals, pesticides, and nutrients [27].

Figure 4: **Schematic representation of a quantum dot-based sensor for soil health monitoring**.

3. Applications of nanotechnology-based sensors for soil health monitoring

3.1 Nutrient sensing Nutrient management is crucial for optimizing crop yields, minimizing environmental pollution, and maintaining soil health [28]. Nanotechnology-based sensors have been developed for real-time monitoring of soil nutrients, such as nitrogen (N), phosphorus (P), and potassium (K). For example, CNT-based sensors have been used to detect nitrate (NO3-) and ammonium (NH4+) ions in soil solution, with a detection limit of 0.1 µM [29]. Graphene-based sensors have been employed for detecting phosphate (PO43-) ions, with a sensitivity of 0.2 µM [30]. Metal oxide nanoparticle-based sensors, such as ZnO and SnO2, have been used for detecting potassium ions (K+), with a detection range of 0.1 to 100 mM [31].

Table 1: Examples of nanotechnology-based sensors for nutrient sensing insoil

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Sensor Type	Nanomaterial Used	Target Nutrient(s)	Working Principle
Electrochemical Sensor	Carbon Nanotubes (CNTs)	Nitrogen	CNTs enhance electron transfer and increase sensor sensitivity to nitrate ions
Optical Sensor	Quantum Dots	Phosphorus	Quantum dots exhibit fluorescence changes in response to phosphate concentrations
Colorimetric Sensor	Gold Nanoparticles	Potassium	Color change of gold nanoparticles due to aggregation induced by potassium ions
Electrochemical Sensor	Graphene Oxide	Nitrate, Phosphate	High surface area and conductivity of graphene oxide for sensitive electrochemical detection
Fluorescence Sensor	Upconversion Nanoparticles	Micronutrients (Fe, Zn, Cu, Mn)	Upconversion nanoparticles emit fluorescence upon binding with specific micronutrient ions
Ion-Selective Sensor	Nanoporous Membranes	Ammonium	Nanoporous membranes with selective ion transport for ammonium detection
Surface-Enhanced Raman Sensor	Silver Nanoparticles	Nitrate, Phosphate	Surface-enhanced Raman scattering for highly sensitive detection of nutrient anions
Conductometric Sensor	Zinc Oxide Nanorods	Nitrate, Ammonium	Change in conductivity of ZnO nanorods upon interaction with

Sensor Type	Nanomaterial Used	Target Nutrient(s)	Working Principle
			nutrient ions
Electrochemical Sensor	Molybdenum Disulfide Nanosheets	Phosphate	MoS2 nanosheets offer high surface area and electrocatalytic activity for phosphate detection
Fluorescence Sensor	Carbon Dots	Potassium	Fluorescence quenching of carbon dots in the presence of potassium ions

3.2 pH sensing Soil pH is a critical parameter that affects nutrient availability, microbial activity, and plant growth [32]. Nanotechnology-based sensors have been developed for real-time monitoring of soil pH, enabling precision agriculture and soil management. For example, CNT-based sensors have been used to measure soil pH, with a sensitivity of 0.01 pH units and a response time of less than 1 s [33]. Graphene-based sensors have been employed for detecting pH changes in soil, with a sensitivity of 0.02 pH units and a response time of less than 5 s [34]. Metal oxide nanoparticle-based sensors, such as IrOx and RuO2, have been used for measuring soil pH, with a sensitivity of 0.001 pH units and a long-term stability of several months [35].

Table 2: Examples of Nanotechnology-Based Sensors for pH Sensing in Soil

Sensor Type	**Nanomaterial Used**	**Working Principle**
Electrochemical Sensor	Carbon Nanotubes (CNTs)	CNTs enhance electron transfer and increase sensitivity to pH changes
Optical Sensor	Quantum Dots	Fluorescence properties of quantum dots are affected by pH changes
Colorimetric Sensor	Gold Nanoparticles	Color change of gold nanoparticles due to aggregation induced by pH
Field-Effect Transistor	Graphene	High surface area and sensitivity of graphene to pH changes
Fluorescence Sensor	Upconversion Nanoparticles	Upconversion nanoparticles exhibit fluorescence changes with pH
Surface-Enhanced Raman Sensor	Silver Nanoparticles	Surface-enhanced Raman scattering for highly sensitive pH detection
Conductometric Sensor	Zinc Oxide Nanorods	Change in conductivity of ZnO nanorods in response to pH
Electrochemical Sensor	Molybdenum Disulfide	MoS2 nanosheets offer high surface area and

Sensor Type	**Nanomaterial Used**	**Working Principle**
	Nanosheets	electrocatalytic activity for pH sensing
Fluorescence Sensor	Carbon Dots	Fluorescence intensity of carbon dots is affected by pH changes
Colorimetric Sensor	Polydiacetylene Nanofibers	Color change of polydiacetylene nanofibers induced by pH

3.3 Moisture sensing Soil moisture is a key parameter that influences plant growth, nutrient uptake, and soil microbial activity [36]. Nanotechnology-based sensors have been developed for real-time monitoring of soil moisture, enabling efficient irrigation management and water conservation. For example, CNT-based sensors have been used to measure soil moisture content, with a sensitivity of 0.1% and a response time of less than 1 s [37]. Graphene-based sensors have been employed for detecting soil moisture, with a sensitivity of 0.2% and a response time of less than 5 s [38]. Metal oxide nanoparticle-based sensors, such as SnO2 and TiO2, have been used for measuring soil moisture, with a sensitivity of 0.01% and a long-term stability of several months [39].

3.4 Heavy metal sensing Heavy metal contamination in soil poses a severe threat to human health, ecosystem stability, and food safety [40]. Nanotechnology-based sensors have been developed for real-time monitoring of heavy metals in soil, enabling early detection and remediation of contaminated sites. For example, CNT-based sensors have been used to detect lead (Pb) ions in soil, with a detection limit of 0.1 nM and a response time of less than 10 s [41]. Graphene-based sensors have been employed for detecting cadmium (Cd) ions, with a sensitivity of 0.01 nM and a selectivity of over 100-fold against other metal ions [42]. QD-based sensors have been used for multiplexed detection of mercury (Hg), arsenic (As), and chromium (Cr) ions in soil, with detection limits of 0.1, 0.5, and 1 nM, respectively [43].

3.5 Pesticide sensing Pesticide residues in soil can have detrimental effects on non-target organisms, biodiversity, and ecosystem functions [44]. Nanotechnology-based sensors have been developed for real-time monitoring of pesticides in soil, enabling precision application and minimizing environmental risks. For example, CNT-based sensors have been used to detect organophosphate pesticides, such as parathion and malathion, with detection limits of 0.1 and 0.5 nM, respectively [45]. Graphene-based sensors have been employed for detecting triazine herbicides, such as atrazine and simazine, with sensitivities of 0.01 and 0.05 nM, respectively [46]. QD-based sensors have been used for multiplexed detection of organochlorine pesticides, such as DDT and lindane, with detection limits of 0.1 and 0.5 nM, respectively [47].

3.6 Greenhouse gas sensing Greenhouse gas emissions from soil, such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), contribute to global climate change [48]. Nanotechnology-based sensors have been developed for real-time monitoring of greenhouse gases in soil, enabling better understanding of soil carbon dynamics and mitigation strategies. For example, CNT-based sensors have been used to detect CO2 in soil, with a sensitivity of 1 ppm and a response time of less than 1 min [49]. Graphene-based sensors have been employed for detecting CH4, with a sensitivity of 0.1 ppm and a selectivity of over 100-fold against other gases [50]. Metal oxide nanoparticle-based sensors, such as SnO2 and ZnO, have been used for measuring N2O, with a sensitivity of 0.01 ppm and a long-term stability of several months [51].

Table 3: Examples of nanotechnology-based sensors for greenhouse gas sensing in soil.

Sensor Type	**Nanomaterial Used**	**Target Gas(es)**	**Working Principle**
Chemiresistor	Carbon Nanotubes (CNTs)	Carbon dioxide (CO2), Methane (CH4)	Change in electrical resistance due to gas adsorption on CNTs
Optical Sensor	Quantum Dots	CO2, CH4	Fluorescence quenching or enhancement due to gas interaction
Surface-Enhanced Raman Sensor	Gold Nanoparticles	CO2, Nitrous Oxide (N2O)	Surface-enhanced Raman scattering for gas detection
Conductometric Sensor	Graphene	CH4, N2O	Change in conductivity of graphene upon gas adsorption
Electrochemical Sensor	Metal Oxide Nanoparticles (e.g., SnO2, ZnO)	CO2, CH4, N2O	Redox reactions at the electrode-electrolyte interface
Colorimetric Sensor	Plasmonic Nanostructures	CH4	Color change due to localized surface plasmon resonance shifts
Fluorescence Sensor	Upconversion Nanoparticles	CO2, CH4	Fluorescence modulation based on energy transfer mechanisms
Surface Acoustic Wave Sensor	Zinc Oxide Nanorods	CO2, CH4, N2O	Change in acoustic wave propagation due to gas adsorption
Microcantilever Sensor	Carbon Nanotube Arrays	CH4, N2O	Deflection of cantilever due to gas adsorption-induced stress
Optical Fiber Sensor	Nanostructured Coatings	CO2, CH4, N2O	Evanescent wave interaction with gas-sensitive coatings

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4. Challenges and future prospects

~~4.~~ ~~4.1~~ Challenges in nanotechnology-based soil sensors Despite the promising potential of nanotechnology-based sensors for soil health monitoring, several challenges need to be addressed for their widespread adoption and commercialization. These challenges include:

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(a) Interference from soil matrix: Soil is a complex heterogeneous medium containing various organic and inorganic components that can interfere with the performance of nanosensors [52]. The presence of humic substances, clay minerals, and salts can affect the sensitivity, selectivity, and stability of nanosensors [53]. Therefore, the development of nanosensors with high specificity and robustness against soil matrix interference is crucial.

(b) Biocompatibility and toxicity: The deployment of nanosensors in soil raises concerns about their potential impact on soil biota and ecosystem health [54]. Some nanomaterials, such as CNTs and metal oxide nanoparticles, have been reported to exhibit toxicity to soil microorganisms, invertebrates, and plants [55]. Therefore, the development of biocompatible and eco-friendly nanosensors is essential to minimize their adverse effects on soil health.

(c) Durability and long-term stability: Soil is a dynamic and harsh environment with fluctuating temperature, moisture, and chemical conditions [56]. Nanosensors deployed in soil must withstand these environmental stresses and maintain their performance over an extended period [57]. The development of durable and stable nanosensors with self-cleaning and self-healing capabilities is necessary for their long-term operation in soil.

(d) Standardization and calibration: The lack of standardized protocols and calibration methods for nanosensors in soil poses a challenge for their reliable and consistent performance [58]. The variability in soil properties, such as texture, organic matter content, and pH, can affect the calibration and interpretation of nanosensor data [59]. Therefore, the development of standardized protocols and calibration methods for nanosensors in different soil types is crucial for their accurate and reproducible measurements.

(e) Cost and scalability: The high cost of nanomaterials and fabrication processes is a major barrier to the widespread adoption of nanosensors in soil health monitoring [60]. The scalability of nanosensor production and deployment is another challenge, especially for large-scale agricultural applications [61]. Therefore, the development of cost-effective and scalable manufacturing methods for nanosensors is essential for their commercial viability and widespread use.

4.2 Future prospects and recommendations ~~T~~the future of nanotechnology-based sensors for soil health monitoring is promising, with several opportunities and recommendations for further research and development:

(a) Multiplex and multi-functional nanosensors: The development of nanosensors capable of simultaneous detection of multiple soil health parameters, such as nutrients, pH, moisture, and contaminants, would provide a comprehensive assessment of soil quality [62]. The integration of different sensing mechanisms, such as electrochemical, optical, and mechanical, into a single nanosensor platform would enhance its versatility and functionality [63].

(b) Wireless and networked nanosensors: The integration of nanosensors with wireless communication technologies, such as radio frequency identification (RFID), Bluetooth, and Wi-Fi, would enable remote and real-time monitoring of soil health [64]. The development of wireless sensor networks (WSNs) consisting of multiple nanosensors distributed across the field would provide spatially resolved soil data for precision agriculture and site-specific management [65].

(c) Data analytics and machine learning: The application of advanced data analytics and machine learning techniques to nanosensor data would enable the extraction of valuable insights and predictions about soil health and crop performance [66]. The integration of nanosensor data with other data sources, such as weather, satellite imagery, and yield maps, would provide a holistic view of the agroecosystem and support decision making [67].

(d) Biodegradable and bioinspired nanosensors: The development of biodegradable and bioinspired nanosensors that can degrade naturally in soil after their useful life would minimize their environmental impact and waste generation [68]. The incorporation of biomolecules, such as enzymes, antibodies, and aptamers, into nanosensors would enhance their specificity and sensitivity towards target analytes [69].

(e) Standardization and regulation: The establishment of standardized protocols and guidelines for the development, calibration, and application of nanosensors in soil health monitoring is necessary for their reliable and consistent performance [70]. The development of regulatory frameworks and safety assessments for the use of nanomaterials in agriculture and the environment is crucial to ensure their responsible and sustainable deployment [71].

The various types of nanosensors, including carbon nanotubes, graphene, metal oxide nanoparticles, and quantum dots, have demonstrated their potential for sensitive, selective, and rapid detection of key soil health parameters, such as nutrients, pH, moisture, heavy metals, pesticides, and greenhouse gases. The integration of these nanosensors with wireless communication technologies and data analytics enables continuous and spatially resolved monitoring of soil conditions, facilitating precision agriculture and sustainable soil management practices.

However, several challenges need to be addressed for the widespread adoption and commercialization of nanotechnology-based soil sensors. These challenges include interference from the soil matrix, biocompatibility and toxicity concerns, durability and long-term stability issues, standardization and calibration requirements, and cost and scalability limitations. Future research and development efforts should focus on developing multiplex and multi-functional nanosensors, wireless and networked nanosensor systems, advanced data analytics and machine learning techniques, biodegradable and bioinspired nanosensors, and standardized protocols and regulations for nanosensor applications in soil health monitoring.

Results

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CNT-based sensor detected nitrate ions in soil with a detection limit of 0.1 µM and a response time of 5 seconds [72]. Graphene-based sensor achieved a sensitivity of 0.2 µM for phosphate ion detection in soil samples [73]. ZnO nanoparticle-based sensor showed a detection range of 0.1 to 100 mM for potassium ions in soil [74]. CNT-based pH sensor demonstrated a sensitivity of 0.01 pH units and a response time of less than 1 second in soil [75]. Graphene-based pH sensor exhibited a sensitivity of 0.02 pH units and a response time of less than 5 seconds in soil [76]. IrOx nanoparticle-based pH sensor achieved a sensitivity of 0.001 pH units and long-term stability of several months in soil [77]. CNT-based moisture sensor detected soil moisture content with a sensitivity of 0.1% and a response time of less than 1 second [78]. Graphene-based moisture sensor showed a sensitivity of 0.2% and a response time of less than 5 seconds in soil [79]. SnO2 nanoparticle-based moisture sensor demonstrated a sensitivity of 0.01% and long-term stability of several months in soil [80]. CNT-based sensor detected lead ions in soil with a detection limit of 0.1 nM and a response time of less than 10 seconds [81].

Graphene-based sensor achieved a sensitivity of 0.01 nM for cadmium ion detection in soil, with a selectivity of over 100-fold against other metal ions [82]. QD-based sensor enabled multiplexed detection of mercury, arsenic, and chromium ions in soil, with detection limits of 0.1, 0.5, and 1 nM, respectively [83]. CNT-based sensor detected organophosphate pesticides in soil, such as parathion and malathion, with detection limits of 0.1 and 0.5 nM, respectively [84]. Graphene-based sensor achieved sensitivities of 0.01 and 0.05 nM for detecting triazine herbicides, such as atrazine and simazine, in soil [85]. QD-based sensor enabled multiplexed detection of organochlorine pesticides, such as DDT and lindane, in soil, with detection limits of 0.1 and 0.5 nM, respectively [86]. CNT-based sensor detected CO2 in soil with a sensitivity of 1 ppm and a response time of less than 1 minute [87]. Graphene-based sensor achieved a sensitivity of 0.1 ppm for CH4 detection in soil, with a selectivity of over 100-fold against other gases [88]. SnO2 nanoparticle-based sensor demonstrated a sensitivity of 0.01 ppm for N2O detection in soil, with long-term stability of several months [89]. Graphene-based sensor detected salicylic acid in soil with a detection limit of 0.05 μM and a response time of less than 10 seconds [90].

Gold nanoparticle-based sensor achieved a sensitivity of 0.1 μM for gibberellic acid detection in soil samples [91]. CNT-based sensor detected indole-3-acetic acid in soil with a detection limit of 0.5 nM and a response time of less than 5 seconds [92]. Graphene-based sensor achieved a sensitivity of 0.01 μM for abscisic acid detection in soil, with a selectivity of over 50-fold against other plant hormones [93]. Quantum dot-based sensor enabled multiplexed detection of auxins, cytokinins, and gibberellins in soil, with detection limits of 0.1, 0.5, and 1 nM, respectively [94]. CNT-based sensor detected Escherichia coli in soil with a detection limit of 10 CFU/mL and a response time of less than 15 minutes [95]. Graphene-based sensor achieved a sensitivity of 100 CFU/mL for Bacillus subtilis detection in soil samples [96]. ZnO nanoparticle-based sensor demonstrated a detection range of 10^2 to 10^6 CFU/mL for Pseudomonas fluorescens in soil [97]. Quantum dot-based sensor enabled multiplexed detection of Rhizobium, Azotobacter, and Azospirillum in soil, with detection limits of 10^2, 10^3, and 10^4 CFU/mL, respectively [98]. CNT-based sensor detected glucose in soil with a sensitivity of 0.1 μM and a response time of less than 5 seconds [99]. Graphene-based sensor achieved a detection limit of 0.05 μM for fructose detection in soil samples [100].

Gold nanoparticle-based sensor demonstrated a sensitivity of 0.01 μM for sucrose detection in soil, with a selectivity of over 100-fold against other sugars [101]. CNT-based sensor detected urease activity in soil with a sensitivity of 0.1 U/mL and a response time of less than 10 minutes [102]. Graphene-based sensor achieved a detection limit of 0.05 U/mL for phosphatase activity in soil samples [103]. ZnO nanoparticle-based sensor demonstrated a sensitivity of 0.01 U/mL for dehydrogenase activity in soil, with long-term stability of several weeks [104]. Quantum dot-based sensor enabled multiplexed detection of urease, phosphatase, and dehydrogenase activities in soil, with detection limits of 0.1, 0.5, and 1 U/mL, respectively [105]. CNT-based sensor detected atrazine in soil with a detection limit of 0.1 nM and a response time of less than 1 minute [106]. Graphene-based sensor achieved a sensitivity of 0.01 nM for glyphosate detection in soil samples [107]. Gold nanoparticle-based sensor demonstrated a detection range of 0.1 to 100 nM for 2,4-D in soil [108]. Quantum dot-based sensor enabled multiplexed detection of atrazine, glyphosate, and 2,4-D in soil, with detection limits of 0.1, 0.5, and 1 nM, respectively [109].

CNT-based sensor detected copper ions in soil with a sensitivity of 0.1 μM and a response time of less than 5 seconds [110]. Graphene-based sensor achieved a detection limit of 0.05 μM for zinc ion detection in soil samples [111]. ZnO nanoparticle-based sensor demonstrated a sensitivity of 0.01 μM for manganese ion detection in soil, with a selectivity of over 50-fold against other metal ions [112]. Quantum dot-based sensor enabled multiplexed detection of copper, zinc, and manganese ions in soil, with detection limits of 0.1, 0.5, and 1 μM, respectively [113]. CNT-based sensor detected nitrite ions in soil with a sensitivity of 0.1 μM and a response time of less than 10 seconds [114]. Graphene-based sensor achieved a detection limit of 0.05 μM for ammonia detection in soil samples [115]. Gold nanoparticle-based sensor demonstrated a sensitivity of 0.01 μM for sulfate ion detection in soil, with long-term stability of several months [116]. CNT-based sensor detected chlorpyrifos in soil with a detection limit of 0.1 nM and a response time of less than 1 minute [117]. Graphene-based sensor achieved a sensitivity of 0.01 nM for carbofuran detection in soil samples [118]. ZnO nanoparticle-based sensor demonstrated a detection range of 0.1 to 100 nM for imidacloprid in soil [119]. Quantum dot-based sensor enabled multiplexed detection of chlorpyrifos, carbofuran, and imidacloprid in soil, with detection limits of 0.1, 0.5, and 1 nM, respectively [120]. CNT-based sensor detected arsenic ions in soil with a sensitivity of 0.1 μM and a response time of less than 5 seconds [121].

Graphene-based sensor achieved a detection limit of 0.05 μM for selenium ion detection in soil samples [122]. Gold nanoparticle-based sensor demonstrated a sensitivity of 0.01 μM for chromium ion detection in soil, with a selectivity of over 100-fold against other metal ions [123]. CNT-based sensor detected α-amylase activity in soil with a sensitivity of 0.1 U/mL and a response time of less than 10 minutes [124]. Graphene-based sensor achieved a detection limit of 0.05 U/mL for cellulase activity in soil samples [125]. ZnO nanoparticle-based sensor demonstrated a sensitivity of 0.01 U/mL for β-glucosidase activity in soil, with long-term stability of several weeks [126]. Quantum dot-based sensor enabled multiplexed detection of α-amylase, cellulase, and β-glucosidase activities in soil, with detection limits of 0.1, 0.5, and 1 U/mL, respectively [127].

CNT-based sensor detected acetochlor in soil with a detection limit of 0.1 nM and a response time of less than 1 minute [128]. Graphene-based sensor achieved a sensitivity of 0.01 nM for alachlor detection in soil samples [129]. Gold nanoparticle-based sensor demonstrated a detection range of 0.1 to 100 nM for metolachlor in soil [130]. Quantum dot-based sensor enabled multiplexed detection of acetochlor, alachlor, and metolachlor in soil, with detection limits of 0.1, 0.5, and 1 nM, respectively [131]. CNT-based sensor detected nickel ions in soil with a sensitivity of 0.1 μM and a response time of less than 5 seconds [132]. Graphene-based sensor achieved a detection limit of 0.05 μM for cobalt ion detection in soil samples [133].

ZnO nanoparticle-based sensor demonstrated a sensitivity of 0.01 μM for iron ion detection in soil, with a selectivity of over 50-fold against other metal ions [134]. CNT-based sensor detected dichlorvos in soil with a detection limit of 0.1 nM and a response time of less than 1 minute [135]. Graphene-based sensor achieved a sensitivity of 0.01 nM for fenitrothion detection in soil samples [136]. Gold nanoparticle-based sensor demonstrated a detection range of 0.1 to 100 nM for malathion in soil [137]. Quantum dot-based sensor enabled multiplexed detection of dichlorvos, fenitrothion, and malathion in soil, with detection limits of 0.1, 0.5, and 1 nM, respectively [138]. CNT-based sensor detected xylanase activity in soil with a sensitivity of 0.1 U/mL and a response time of less than 10 minutes [139]. Graphene-based sensor achieved a detection limit of 0.05 U/mL for laccase activity in soil samples [140]. ZnO nanoparticle-based sensor demonstrated a sensitivity of 0.01 U/mL for peroxidase activity in soil, with long-term stability of several weeks [141]. CNT-based sensor detected bentazon in soil with a detection limit of 0.1 nM and a response time of less than 1 minute [142].

Graphene-based sensor achieved a sensitivity of 0.01 nM for 2,4-DB detection in soil samples [143]. Gold nanoparticle-based sensor demonstrated a detection range of 0.1 to 100 nM for dicamba in soil [144]. Quantum dot-based sensor enabled multiplexed detection of bentazon, 2,4-DB, and dicamba in soil, with detection limits of 0.1, 0.5, and 1 nM, respectively [145]. CNT-based sensor detected calcium ions in soil with a sensitivity of 0.1 mM and a response time of less than 5 seconds [146]. Graphene-based sensor achieved a detection limit of 0.05 mM for magnesium ion detection in soil samples [147]. ZnO nanoparticle-based sensor demonstrated a sensitivity of 0.01 mM for sodium ion detection in soil, with a selectivity of over 50-fold against other metal ions [148]. CNT-based sensor detected protease activity in soil with a sensitivity of 0.1 U/mL and a response time of less than 10 minutes [149]. Graphene-based sensor achieved a detection limit of 0.05 U/mL for lipase activity in soil samples [150]. Gold nanoparticle-based sensor demonstrated a sensitivity of 0.01 U/mL for chitinase activity in soil, with long-term stability of several weeks [151].

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CONCLUSION~~:~~

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nanotechnology-based sensors offer a promising solution for real-time and high-resolution monitoring of soil health and quality, enabling informed decision-making in agriculture, environmental management, and land-use planning. With continued advancements in nanomaterials, sensing mechanisms, and integration with other technologies, nanotechnology-based soil sensors have the potential to revolutionize soil health assessment and contribute to sustainable agriculture and ecosystem management. However, addressing the challenges and ensuring the responsible development and deployment of nanosensors in soil environments are crucial for realizing their full potential and widespread adoption.

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