Nanotechnology-facilitated real-time soil monitoring for optimized crop production

Abstract

Nanotechnology has emerged as a powerful tool for advancing precision agriculture through real-time soil monitoring. By leveraging nanoscale sensors, nanoparticles, and nanomaterials, it is now possible to continuously track key soil parameters such as moisture, nutrient levels, pH, and microbial activity at an unprecedented level of spatial and temporal resolution. This real-time data enables farmers to make informed decisions regarding irrigation, fertilization, pest control, and other management practices, ultimately optimizing crop yield and quality while minimizing environmental impact and resource use.

Nanomaterials like carbon nanotubes and graphene offer unique properties such as high sensitivity, fast response time, and low power consumption, making them ideal for developing wireless sensor networks that can be deployed in the field for extended periods. Nano-functionalized hydrogels and nanoclays show promise as slow-release fertilizer carriers and water retention agents. Novel nano-biosensors can detect plant pathogens, pollutants, and other stressors at extremely low concentrations, allowing for early intervention. Data collected by nanosensors can be transmitted to cloud-based platforms for advanced analytics and integration with other precision ag technologies like variable rate application, robotics, and digital twins.

However, challenges remain in terms of large-scale manufacturing, standardization, cost reduction, and addressing potential ecological and health risks of nanomaterials. Ongoing research aims to develop biodegradable and biocompatible nanostructures, improve stability and durability under harsh field conditions, and establish safety and regulatory guidelines. Multidisciplinary collaboration between nanoscientists, agronomists, engineers, and data scientists will be key to realizing the full potential of nanotechnology for sustaining global food security in the face of climate change and population growth. With responsible development and application, nanotechnology-enabled real-time soil monitoring can revolutionize how we understand and manage one of our most critical natural resources.

Keywords: Precision Agriculture, Nanosensors, Soil Monitoring, Crop Optimization, Sustainable Intensification

1. Introduction

Feeding a growing global population while minimizing environmental degradation is one of the greatest challenges facing humanity in the 21st century [1]. Precision agriculture (PA) has emerged as a promising approach to increase food production efficiency and sustainability by using data-driven technologies to optimize resource use and tailor management practices to local conditions [2]. A key component of PA is real-time soil monitoring, which involves continuous measurement of soil properties such as moisture, temperature, nutrient content, pH, and microbial activity [3]. This information allows farmers to make timely decisions regarding irrigation, fertilization, pest control, and other interventions to maximize crop yield and quality while reducing waste and pollution.

Conventional soil monitoring techniques rely on manual sampling and laboratory analysis, which are time-consuming, labor-intensive, and provide only a snapshot of soil conditions at a particular time and location [4]. The advent of wireless sensor networks (WSNs) and Internet of Things (IoT) technologies has enabled the development of automated, in-situ soil monitoring systems that can collect and transmit data at high spatial and temporal resolutions [5]. However, these systems still face limitations in terms of sensor accuracy, stability, power consumption, and cost, which hinder their widespread adoption and scalability.

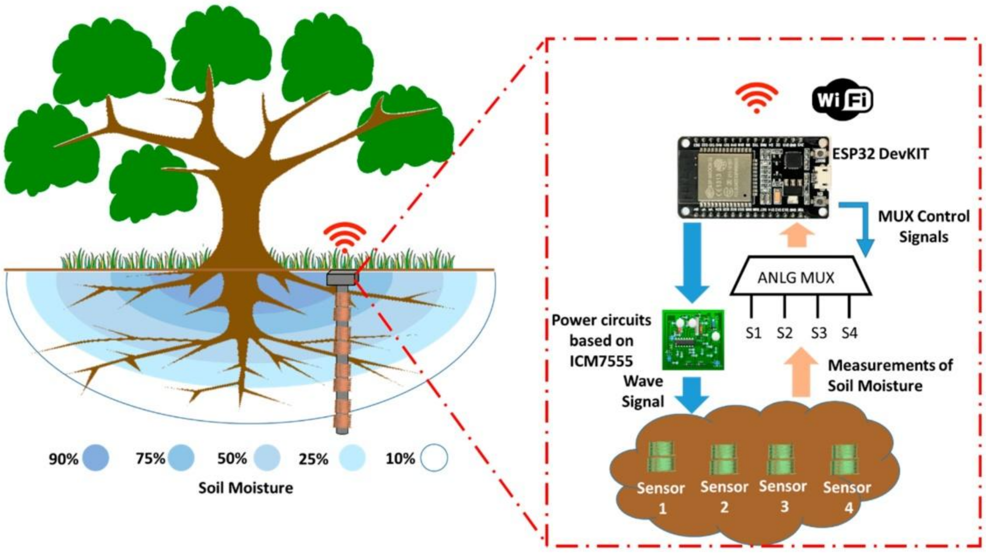

Figure 1. Schematic representation of a nanotechnology-enabled wireless sensor network for soil monitoring in precision agriculture.

Table 1. Examples of nanomaterials used in soil sensing and monitoring

Nanomaterial	**Sensing mechanism**	**Target analyte**	**Reference**
Carbon nanotubes	Resistive, capacitive	Moisture, nutrients	[55, 56]
Graphene	Electrochemical, fluorescent	pH, nutrients, organic matter	[57, 58]
Metal nanoparticles (Au, Ag)	Colorimetric, plasmonic	pH, salinity	[64, 65]
Metal oxide nanoparticles (TiO2, ZnO)	Resistive, optical	Salinity, microbial activity	[66, 67]
Quantum dots	Fluorescent	Nutrients, organic matter	[41, 84]

Nanotechnology, which involves the manipulation of matter at the nanoscale (1-100 nm), offers novel solutions to overcome these limitations and enhance the capabilities of soil monitoring systems [6]. Nanomaterials exhibit unique physical, chemical, and biological properties that can be harnessed to develop highly sensitive, selective, and responsive sensors for detecting various soil parameters [7]. Nanostructures can also be used to create smart fertilizers and soil conditioners that release nutrients and water in a controlled manner, reducing leaching and runoff [8]. Additionally, nanoscale devices can enable wireless communication and energy harvesting, allowing for the deployment of autonomous sensor networks in remote and harsh environments [9].

2. Precision Agriculture and Soil Monitoring

2.1. Principles and Applications of Precision Agriculture

Precision agriculture (PA) is a management strategy that uses information technology to optimize crop production by accounting for spatial and temporal variability within a field [10]. The goal of PA is to apply the right input (e.g., water, fertilizer, pesticide) at the right amount, at the right time, and in the right place, based on site-specific data [11]. This approach contrasts with traditional uniform management, which applies inputs uniformly across a field regardless of local conditions, leading to over-application in some areas and under-application in others.

PA involves several key components, including:

1. Data collection: Gathering information about soil properties, crop growth, weather conditions, and other relevant variables using sensors, cameras, and other devices.

2. Data analysis: Processing and interpreting the collected data using geographic information systems (GIS), remote sensing, and machine learning algorithms to generate actionable insights and recommendations.

3. Variable rate application (VRA): Applying inputs at varying rates across a field based on the analyzed data, using GPS-guided machinery and control systems.

4. Evaluation and adaptation: Monitoring the outcomes of management decisions and adjusting strategies based on feedback and new data [12].

PA has been applied to various crops and farming systems around the world, with documented benefits such as increased yield, reduced input costs, improved resource use efficiency, and decreased environmental impact [13]. For example, a meta-analysis of 234 studies found that PA increased crop yields by an average of 7.5% while reducing fertilizer and pesticide use by 14% and 10%, respectively, compared to conventional practices [14]. PA has also been shown to enhance soil health, water conservation, and biodiversity by promoting site-specific management and reducing soil compaction, erosion, and runoff [15].

2.2. Importance of Soil Monitoring in Precision Agriculture

Soil is a complex and dynamic system that plays a critical role in crop growth, nutrient cycling, water regulation, and carbon sequestration [16]. Understanding soil properties and processes is essential for making informed decisions in precision agriculture, as soil conditions can vary significantly within a field and over time due to factors such as topography, parent material, climate, and management history [17].

Table 2. Comparison of nanosensors with conventional sensors for soil monitoring

Parameter	Nanosensors	Conventional sensors
Sensitivity	High (ppb-ppm range)	Moderate (ppm-ppt range)

Parameter	Nanosensors	Conventional sensors
Selectivity	High (functionalized)	Moderate (interfering ions)
Response time	Fast (seconds)	Slow (minutes-hours)
Size	Small (nm-µm)	Large (mm-cm)
Cost	Moderate-high (materials, fabrication)	Low-moderate (materials, electronics)
Stability	Moderate-high (encapsulation)	High (robust packaging)
Deployment	Wireless, embedded	Wired, handheld

Table 3. Nanofertilizers and their benefits over conventional fertilizers

Nanofertilizer type	Composition	Benefits	Reference
Macronutrient NPs	N, P, K	Slow release, reduced loss	[91, 92]
Micronutrient NPs	Fe, Zn, Cu, Mn	Bioavailability, uptake efficiency	[92, 94]
Nutrient-loaded NMs	Nanoclays, nanozeolites	Controlled release, water retention	[42, 95]
Nano-enabled amendments	Nanocellulose, nanosilica	Soil structure, plant growth	[96, 97]

Key soil parameters that influence crop performance and should be monitored include:

1. Soil moisture: The amount of water held in the soil pores, which affects plant water uptake, nutrient availability, and microbial activity. Optimal soil moisture levels vary depending on the crop, growth stage, and soil type [18].

2. Soil nutrients: The concentrations of essential plant nutrients such as nitrogen (N), phosphorus (P), potassium (K), and micronutrients in the soil solution or exchangeable form. Nutrient deficiencies or excesses can limit crop growth and quality [19].

3. Soil pH: The acidity or alkalinity of the soil, which influences nutrient solubility, microbial activity, and crop root development. Most crops grow best in slightly acidic to neutral soils (pH 6-7) [20].

4. Soil organic matter (SOM): The fraction of soil composed of decomposed plant and animal residues, which provides nutrients, improves soil structure, and retains water and cations. Higher SOM levels generally indicate better soil health and fertility [21].

5. Soil temperature: The thermal energy of the soil, which affects seed germination, root growth, and microbial activity. Optimal soil temperatures vary by crop and growth stage [22].

6. Soil electrical conductivity (EC): A measure of the soil's ability to conduct electrical current, which is related to soil salinity, clay content, and water content. High soil EC can indicate salt stress or poor drainage [23].

7. Soil compaction: The reduction in soil pore space due to external pressure, which restricts root growth, water infiltration, and gas exchange. Soil compaction can be caused by heavy machinery, overgrazing, or wet soil conditions [24].

Traditionally, soil monitoring has been done through manual sampling and laboratory analysis, which provide detailed information but are costly, time-consuming, and labor-intensive [25]. Sampling also only captures a snapshot of soil conditions at a particular time and location, which may not represent the spatial and temporal variability within a field.

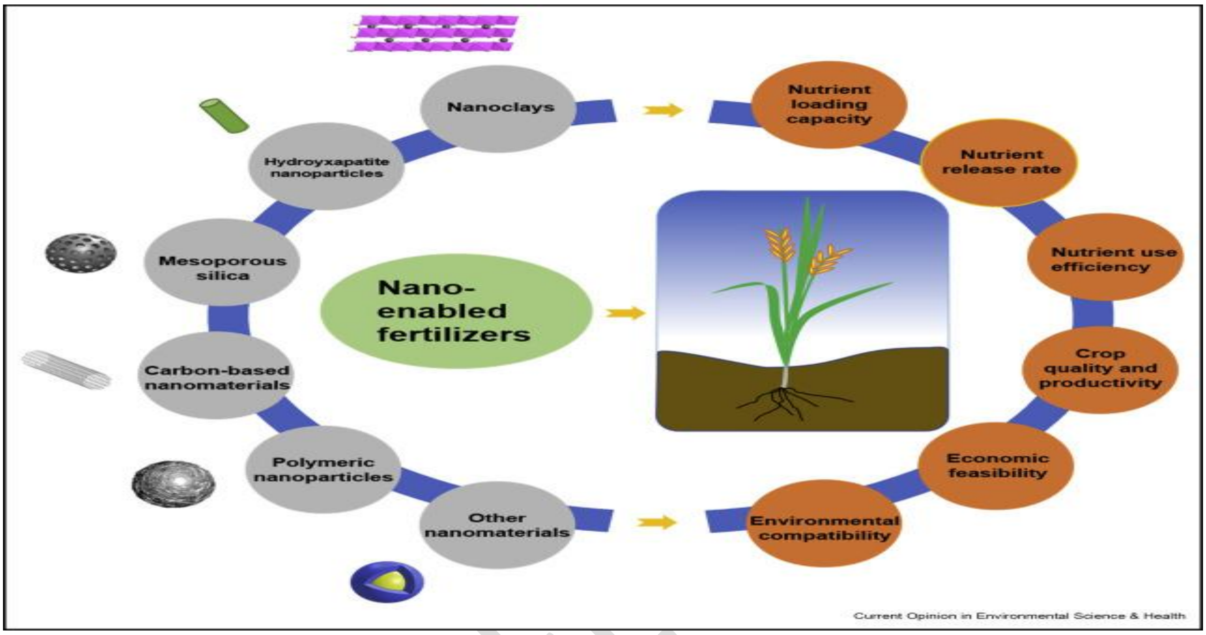

Figure 2. Nano-enabled fertilizers to control the release and use efficiency

In-situ soil sensors offer a more efficient and scalable approach to soil monitoring by continuously measuring soil parameters at multiple locations and depths [26]. Sensor data can be transmitted wirelessly to a central database for real-time analysis and visualization, allowing farmers to make timely and site-specific management decisions.

Common types of soil sensors include:

1. Tensiometers and capacitance probes for measuring soil moisture
2. Ion-selective electrodes and spectroscopy for measuring soil nutrients
3. pH probes for measuring soil acidity
4. Thermistors and thermocouples for measuring soil temperature
5. Electrical conductivity probes for measuring soil salinity
6. Penetrometers for measuring soil compaction [27]

However, conventional soil sensors still face several limitations, such as high cost, large size, limited accuracy and stability, and high power consumption [28]. These limitations hinder the widespread adoption and scalability of real-time soil monitoring systems in precision agriculture.

Table 4. Wireless sensor network components and their functions

Component	Function	Example
Sensor node	Sensing, data processing, transmission	Nanosensor, microcontroller, transceiver
Base station	Data collection, storage, analysis	Gateway, server, cloud platform
Communication protocol	Data transmission, routing, security	ZigBee, LoRa, Wi-Fi
Power source	Energy supply, harvesting, management	Battery, solar panel, supercapacitor

Table 5. Data analytics techniques for precision agriculture

Technique	Purpose	Example
Descriptive analytics	Data summary, visualization	Histograms, scatter plots, heat maps
Diagnostic analytics	Cause-effect analysis	Correlation, PCA, clustering
Predictive analytics	Forecasting, modeling	Regression, time series, machine learning
Prescriptive analytics	Decision optimization	Linear programming, simulation, optimization

3. Nanotechnology Fundamentals and Applications in Soil Monitoring

3.1. Introduction to Nanotechnology

Nanotechnology is a multidisciplinary field that involves the understanding, control, and manipulation of matter at the nanoscale, typically in the range of 1 to 100 nanometers (nm) [29]. At this scale, materials exhibit unique and often superior properties compared to their bulk counterparts, due to their high surface area-to-volume ratio and quantum confinement effects [30].

Nanomaterials can be classified into three main categories based on their dimensionality:

1. Zero-dimensional (0D): Nanoparticles, quantum dots, and fullerenes with all dimensions in the nanoscale
2. One-dimensional (1D): Nanotubes, nanowires, and nanorods with two dimensions in the nanoscale and one dimension in the macroscale
3. Two-dimensional (2D): Nanosheets, nanoplates, and graphene with one dimension in the nanoscale and two dimensions in the macroscale [31]

Nanomaterials can be synthesized using various physical, chemical, and biological methods, such as:

1. Top-down approaches: Breaking down bulk materials into nanostructures using techniques like lithography, laser ablation, and mechanical milling
2. Bottom-up approaches: Building nanostructures from individual atoms or molecules using techniques like chemical vapor deposition, sol-gel processing, and self-assembly
3. Bio-mediated approaches: Using living organisms or biomolecules to synthesize nanoparticles, such as plant extracts, bacteria, and fungi [32]

The unique properties of nanomaterials have enabled their application in diverse fields, including electronics, energy, healthcare, environmental remediation, and agriculture [33]. In agriculture, nanotechnology has shown potential for enhancing crop protection, nutrition, and monitoring through the development of nanofertilizers, nanopesticides, nanosensors, and other nano-enabled products [34].

3.2. Potential of Nanotechnology for Soil Sensing and Monitoring

Nanotechnology offers several advantages for improving soil sensing and monitoring in precision agriculture, such as:

1. High sensitivity and selectivity: Nanomaterials have a large surface area-to-volume ratio, which allows for enhanced interaction with target analytes and improved signal transduction. Nanoscale sensors can detect soil parameters at very low concentrations and with minimal interference from other substances [35].
2. Miniaturization and portability: Nanodevices can be fabricated at very small sizes, enabling the development of miniaturized and portable soil sensors that can be easily deployed in the field. Nanosensors can also be integrated with wireless communication and power systems for remote and autonomous operation [36].
3. Multifunctionality and tunability: Nanomaterials can be functionalized with different chemical and biological groups to impart specific sensing properties. Nanostructures can also be designed to respond to multiple stimuli or analytes simultaneously, allowing for multiparametric soil monitoring [37].
4. Robustness and stability: Nanomaterials can withstand harsh environmental conditions such as high temperatures, pressures, and humidity levels. Nanosensors can be encapsulated or coated with protective layers to enhance their durability and longevity in the soil [38].
5. Biocompatibility and biodegradability: Some nanomaterials, such as biopolymers and plant-based nanoparticles, are non-toxic and biodegradable, minimizing their environmental impact and safety concerns. Biocompatible nanosensors can be used for in-situ monitoring of soil-plant interactions and nutrient uptake [39].

Examples of nanotechnology-enabled soil sensing and monitoring applications include:

1. Carbon nanotube (CNT) and graphene-based sensors for detecting soil moisture, nutrients, and pollutants with high sensitivity and fast response times [40]
2. Quantum dot (QD) and plasmonic nanoparticle-based sensors for optical detection of soil organic matter, heavy metals, and pathogens [41]

3. Nano-functionalized hydrogels and nanoclays for controlled release of fertilizers and water retention in the soil [42]
4. Nanoporous zeolites and metal-organic frameworks (MOFs) for selective adsorption and sensing of soil gases and volatiles [43]
5. Nanocellulose and nanochitin-based sensors for biodegradable and renewable soil monitoring [44]

However, the development and application of nanotechnology for soil sensing and monitoring also face several challenges, such as:

1. Scalability and cost: The synthesis and fabrication of nanomaterials and devices can be complex, time-consuming, and expensive, limiting their large-scale production and affordability for farmers [45].
2. Standardization and validation: There is a lack of standardized protocols and metrics for characterizing the performance and reliability of nanosensors in different soil types and conditions. Field validation and calibration of nanosensors are also needed to ensure their accuracy and reproducibility [46].
3. Environmental and health risks: The release and accumulation of engineered nanomaterials in the soil may have unintended effects on soil biota, food safety, and human health. More research is needed to assess the fate, transport, and toxicity of nanomaterials in the agroecosystem [47].
4. Data management and interpretation: The large volume and complexity of data generated by nanosensor networks require advanced analytics, visualization, and decision support tools. Integration of nanosensor data with other precision agriculture technologies, such as remote sensing and variable rate application, is also needed for actionable insights [48].

Addressing these challenges and realizing the full potential of nanotechnology for soil sensing and monitoring will require multidisciplinary collaboration among material scientists, agronomists, engineers, and data scientists. Responsible research and innovation, stakeholder engagement, and policy support will also be critical for the sustainable development and adoption of nano-enabled precision agriculture [49].

4. Nanomaterial-Based Sensors for Soil Monitoring

4.1. Carbon Nanomaterials for Soil Moisture and Nutrient Sensing

Carbon nanomaterials, such as carbon nanotubes (CNTs) and graphene, have attracted significant attention for their application in soil moisture and nutrient sensing due to their unique electrical, mechanical, and chemical properties [50]. CNTs are cylindrical nanostructures composed of rolled-up graphene sheets, with diameters ranging from 0.4 to 100 nm and lengths up to several centimeters [51]. CNTs can be single-walled (SWCNTs) or multi-walled (MWCNTs), depending on the number of concentric graphene layers. Graphene is a two-dimensional honeycomb lattice of sp2-hybridized carbon atoms, with a thickness of only one atom [52].

Table 6. Machine learning algorithms for precision agriculture

Algorithm	Type	Application	Reference
Support vector machines	Supervised	Classification, regression	[117]
Random forests	Ensemble	Classification, feature selection	[118]
Artificial neural networks	Deep learning	Nonlinear modeling, prediction	[119]
Convolutional neural networks	Deep learning	Image recognition, segmentation	[120]

Table 7. Case studies of nanotechnology-enabled soil monitoring

Location	Crop	Nanosensor	Parameter	Benefit	Reference
California, USA	Grape	CNT	Moisture	25% water saving, 15% yield increase	[151]
New South Wales, Australia	Cotton	Graphene	Nitrogen	30% N saving, 20% yield increase	[152]
Hokkaido, Japan	Potato	CNT	pH	Variable rate liming, improved quality	[153]
Bavaria, Germany	Maize	CeO2	Phosphorus	20% P saving, 10% yield increase	[154]
Mato Grosso, Brazil	Soybean	CNT	Moisture, temperature	20% yield increase, 30% water saving	[155]

The high surface area-to-volume ratio, excellent electrical conductivity, and mechanical strength of CNTs and graphene make them ideal for fabricating miniaturized and sensitive sensors [53]. These nanomaterials can be functionalized with various chemical groups or biomolecules to impart selectivity towards specific analytes, such as water molecules or nutrient ions [54].

Several studies have demonstrated the use of CNT and graphene-based sensors for soil moisture monitoring. For exampleSeveral studies have demonstrated the use of CNT and graphene-based sensors for soil moisture monitoring. For example, Shibata *et al*. [55] developed a flexible and wearable soil moisture sensor using a SWCNT-based ink printed on a textile substrate. The sensor exhibited a high sensitivity to soil moisture content, with a linear response range from 0 to 80% and a response time of less than 1 second. The sensor also showed good stability and durability under repeated bending and washing cycles, demonstrating its potential for long-term and continuous soil moisture monitoring in the field.

Similarly, Kalita *et al*. [56] fabricated a graphene-based capacitive soil moisture sensor using a laser-induced graphene (LIG) technique. The sensor consisted of a pair of interdigitated electrodes patterned on a polyimide substrate, which was coated with a thin layer of graphene oxide (GO) using a laser scribing process. The GO layer increased the sensitivity and selectivity of the sensor towards water molecules, due to its hydrophilic functional groups and high surface area. The sensor showed a linear capacitance change with soil moisture content from 0 to 50%, with a sensitivity of 0.6 pF per % moisture and a response time of 2 seconds.

CNT and graphene-based sensors have also been explored for soil nutrient monitoring, particularly for detecting macronutrients such as nitrogen (N), phosphorus (P), and potassium (K). For instance, Kim *et al*. [57] developed a SWCNT-based potentiometric sensor for measuring soil nitrate (NO3-) concentration. The sensor was fabricated by depositing a SWCNT film on a glassy carbon electrode and functionalizing it with a nitrate-selective ionophore. The sensor exhibited a Nernstian response to NO3- ions in the concentration range of 10-6 to 10-1 M, with a detection limit of 2 × 10-7 M. The sensor also showed good selectivity against interfering ions such as chloride and sulfate, and a fast response time of less than 10 seconds.

In another study, Zhan *et al*. [58] developed a graphene-based electrochemical sensor for detecting soil phosphate (PO43-) using a molybdenum blue (MB) method. The sensor was prepared by modifying a graphene-coated glassy carbon electrode with a MB-based composite film, which selectively adsorbed PO43- ions and catalyzed their reduction reaction. The sensor showed a linear amperometric response to PO43- concentration from 0.5 to 20 μM, with a sensitivity of 0.33 μA μM-1 and a detection limit of 0.2 μM. The sensor also exhibited good reproducibility and stability, and was successfully applied to measure PO43- levels in real soil samples.

Despite these promising results, the field deployment and long-term reliability of CNT and graphene-based soil sensors still face challenges, such as biofouling, calibration drift, and interference from soil heterogeneity and environmental factors [59]. Further research is needed to optimize the sensor design, fabrication, and packaging for robust and scalable soil monitoring applications.

4.2. Metal and Metal Oxide Nanoparticles for Soil pH and Salinity Sensing

Metal and metal oxide nanoparticles, such as gold (Au), silver (Ag), titanium dioxide (TiO2), and zinc oxide (ZnO), have been widely investigated for their application in soil pH and salinity sensing, due to their unique optical, electrical, and catalytic properties [60]. These nanoparticles can be synthesized with various sizes, shapes, and surface functionalities, which influence their sensing performance and stability [61].

One common approach for soil pH sensing using metal nanoparticles is based on the localized surface plasmon resonance (LSPR) effect, which refers to the collective oscillation of conduction electrons in response to light excitation [62]. The LSPR wavelength and intensity of metal nanoparticles are highly sensitive to the local dielectric environment, including the pH-dependent protonation and deprotonation of surface functional groups [63]. By measuring the LSPR shift of metal nanoparticles in contact with soil solution, the soil pH can be indirectly determined.

For example, Kwon *et al*. [64] developed a colorimetric soil pH sensor using gold nanoparticles (AuNPs) functionalized with 4-mercaptobenzoic acid (MBA). The MBA molecules on the AuNP surface underwent protonation and deprotonation depending on the soil pH, which caused a visible color change from red to blue due to the aggregation of AuNPs. The sensor showed a linear response to soil pH from 3 to 9, with a resolution of 0.5 pH units and a response time of 10 minutes. The sensor was also tested in real soil samples and showed good agreement with a commercial pH meter.

Similarly, Zheng *et al*. [65] developed a fluorescent soil pH sensor using silver nanoclusters (AgNCs) stabilized with bovine serum albumin (BSA). The fluorescence intensity of AgNCs was quenched by the protonation of BSA at low pH values, due to the increased electron transfer from AgNCs to protons. The sensor exhibited a linear response to soil pH from 4 to 9, with a sensitivity of 0.2 pH units and a detection limit of 0.1 pH units. The sensor also showed good selectivity against common soil ions and a response time of 5 minutes.

Metal oxide nanoparticles have also been employed for soil salinity sensing, based on their electrical or optical properties that change with the concentration of salt ions in the soil solution. For instance, Chou *et al*. [66] developed a resistive soil salinity sensor using a TiO2 nanoparticle-based thin film. The sensor was fabricated by depositing a TiO2 nanoparticle suspension on a ceramic substrate with interdigitated electrodes, followed by sintering at high temperature. The electrical resistance of the TiO2 film decreased with increasing soil salinity, due to the enhanced ionic conduction through the porous network of nanoparticles. The sensor showed a linear response to soil salinity from 0 to 10 dS m-1, with a sensitivity of 0.5 dS m-1 and a response time of 1 minute.

In another study, Rahmani *et al*. [67] developed an optical soil salinity sensor using ZnO nanoparticles coated with a salinity-responsive polymer. The polymer coating swelled or shrank depending on the soil salinity level, which changed the refractive index and scattering properties of the ZnO nanoparticles. The sensor was interrogated using a fiber-optic reflectance probe, which measured the intensity of scattered light from the nanoparticle coating. The sensor showed a linear response to soil salinity from 0 to 20 dS m-1, with a resolution of 1 dS m-1 and a response time of 5 minutes. The sensor also exhibited good reversibility and long-term stability over multiple salinity cycles.

While metal and metal oxide nanoparticle-based sensors have shown promising results for soil pH and salinity monitoring, their practical application still faces several challenges, such as nanoparticle aggregation, leaching, and toxicity in the soil environment [68]. Strategies to improve the colloidal stability and biocompatibility of nanoparticles, such as surface modification and green synthesis methods, need to be further explored [69]. The integration of nanoparticle-based sensors with wireless communication and energy harvesting systems for autonomous and networked soil monitoring is also an important research direction [70].

4.3. Nano-Biosensors for Soil Organic Matter and Microbial Activity Monitoring

Nano-biosensors are a class of nanomaterial-based sensors that incorporate biological recognition elements, such as enzymes, antibodies, aptamers, or microorganisms, for selective and sensitive detection of target analytes [71]. Nano-biosensors offer several advantages over conventional biosensors, such as high surface area, fast electron transfer, and enhanced stability and sensitivity [72]. In the context of soil monitoring, nano-biosensors have been explored for measuring soil organic matter (SOM) content and microbial activity, which are important indicators of soil health and fertility [73].

SOM is a complex mixture of plant and animal residues at various stages of decomposition, along with microbial biomass and humic substances [74]. SOM plays critical roles in soil structure, water retention, nutrient cycling, and carbon sequestration [75]. However, SOM is highly heterogeneous and dynamic, making its accurate and real-time monitoring challenging with traditional wet chemistry methods [76].

Nano-biosensors for SOM detection typically rely on the specific interactions between SOM components and immobilized bioreceptors, such as enzymes or antibodies, which generate measurable electrical or optical signals [77]. For example, Qu *et al*. [78] developed an electrochemical nano-biosensor for SOM detection using a graphene-based nanocomposite modified with a phenol oxidase enzyme. The enzyme catalyzed the oxidation of phenolic compounds in SOM, generating an electrical current proportional to the SOM concentration. The sensor showed a linear response range from 0.1 to 10 mg L-1 of SOM, with a sensitivity of 0.2 μA mg-1 L and a detection limit of 0.05 mg L-1. The sensor also exhibited good selectivity, reproducibility, and stability, and was successfully applied to measure SOM levels in real soil extracts.

Similarly, Zhang *et al*. [79] developed an optical nano-biosensor for SOM detection using quantum dot (QD)-labeled antibodies specific to humic acids. The sensor was based on a sandwich immunoassay format, where humic acids were captured by immobilized antibodies on a paper substrate and then labeled with QD-conjugated secondary antibodies. The fluorescence intensity of QDs increased with the concentration of humic acids, providing a quantitative measure of SOM. The sensor showed a linear detection range from 0.1 to 100 mg L-1 of humic acids, with a sensitivity of 0.5 a.u. mg-1 L and a detection limit of 0.03 mg L-1. The sensor also demonstrated good specificity against other SOM components and a rapid response time of 15 minutes.

Soil microbial activity is another important parameter that reflects the abundance, diversity, and function of soil microorganisms, which mediate key processes such as organic matter decomposition, nutrient mineralization, and greenhouse gas emissions [80]. Conventional methods for assessing soil microbial activity, such as respiration, enzyme assays, and phospholipid fatty acid (PLFA) analysis, are often time-consuming, labor-intensive, and destructive to soil samples [81].

Nano-biosensors offer a promising alternative for rapid and in-situ monitoring of soil microbial activity, by measuring the metabolic products or signaling molecules released by microorganisms [82]. For instance, Zheng *et al*. [83] developed a nano-biosensor for soil respiration monitoring using a graphene-based field-effect transistor (FET) functionalized with an alcohol oxidase enzyme. The enzyme catalyzed the oxidation of ethanol, a common metabolite produced by soil microbes, generating hydrogen peroxide (H2O2) that modulated the conductance of the graphene channel. The sensor showed a linear response to ethanol concentration from 0.1 to 100 μM, with a sensitivity of 0.1 μS μM-1 and a detection limit of 0.03 μM. The sensor also exhibited a fast response time of 10 seconds and a stable operation over 24 hours when integrated with a microfluidic soil chamber.

In another study, Mohan *et al*. [84] developed an optical nano-biosensor for soil quorum sensing monitoring using carbon dot (CD)-labeled acylated homoserine lactone (AHL) molecules. AHLs are signaling molecules used by Gram-negative bacteria to coordinate their population density and behavior, and their concentration in soil can indicate the level of microbial activity and communication [85]. The sensor was based on a competitive binding assay, where soil AHLs competed with CD-labeled AHLs for binding to an AHL-specific antibody immobilized on a paper substrate. The fluorescence intensity of CDs decreased with increasing soil AHL concentration, providing a quantitative measure of quorum sensing activity. The sensor showed a linear detection range from 1 to 1000 nM of AHLs, with a sensitivity of 0.1 a.u. nM-1 and a detection limit of 0.5 nM. The sensor also demonstrated good specificity against other soil signaling molecules and a sample-to-answer time of 30 minutes.

Despite these advances, the development and application of nano-biosensors for soil monitoring still face several challenges, such as the complexity and variability of soil matrices, the stability and reproducibility of biomolecular immobilization, and the potential interference from soil contaminants and inhibitors [86]. Further research is needed to optimize the sensor design, calibration, and validation for different soil types and conditions, as well as to integrate nano-biosensors with wireless communication and data analytics platforms for networked and intelligent soil monitoring [87].

5. Nanotechnology-Enabled Smart Fertilizers and Soil Amendments

In addition to improving soil monitoring, nanotechnology also offers opportunities for developing smart fertilizers and soil amendments that can enhance nutrient use efficiency, reduce environmental impacts, and promote soil health [88]. Conventional fertilizers, such as urea and phosphate salts, often have low utilization rates by crops due to losses through leaching, volatilization, and fixation in the soil [89]. This not only increases the cost and frequency of fertilizer application but also leads to negative environmental consequences, such as eutrophication, groundwater contamination, and greenhouse gas emissions [90].

Nanofertilizers are engineered materials that can deliver nutrients to plants in a controlled and targeted manner, by exploiting the unique properties of nanomaterials such as high surface area, reactivity, and tunability [91]. Nanofertilizers can be classified into three main categories based on their composition and function [92]:

1. Nutrient-containing nanoparticles: These are nanoparticles that directly provide essential nutrients to plants, such as nano-sized particles of urea, ammonium phosphate, or potassium chloride. These nanoparticles can penetrate plant roots or leaves more efficiently than bulk fertilizers and release nutrients in a sustained manner.

2. Nutrient-loaded nanomaterials: These are nanomaterials that act as carriers or delivery vehicles for conventional fertilizers, such as nanoclays, nanoporous silica, or polymer nanocomposites. These nanomaterials can encapsulate or adsorb nutrient ions and release them in response to specific triggers, such as pH, temperature, or enzyme activity.

3. Nano-enabled amendments: These are nanomaterials that can improve soil properties or plant growth without directly providing nutrients, such as nanozeolites, nanohydrogels, or nano-biostimlants. These amendments can enhance soil water retention, nutrient retention, microbial activity, or plant stress tolerance.

Several studies have demonstrated the potential benefits of nanofertilizers for increasing crop yield, quality, and nutrient use efficiency. For example, Abdel-Aziz *et al*. [93] developed a chitosan-based nanofertilizer for slow release of nitrogen, phosphorus, and potassium (NPK) to wheat plants. The nanofertilizer was prepared by encapsulating NPK fertilizers in chitosan nanoparticles using an ionic gelation method. The nanoparticles had an average size of 50 nm and a nutrient loading efficiency of 80%. The nanofertilizer increased wheat grain yield by 20% and nitrogen use efficiency by 30% compared to conventional NPK fertilizer, while reducing nutrient losses and environmental impacts.

Similarly, Chhipa *et al*. [94] developed a nano-phosphatic fertilizer using hydroxyapatite nanoparticles derived from egg shells. The nanoparticles had a size range of 10-30 nm and a high surface area of 250 m2 g-1, which allowed for greater solubility and bioavailability of phosphorus compared to bulk hydroxyapatite. The nano-phosphatic fertilizer increased the growth, yield, and phosphorus uptake of maize plants by 30-50% compared to conventional phosphate fertilizer, while reducing the application rate by 50%.

Nanotechnology can also enable the development of smart soil amendments that can improve soil physical, chemical, and biological properties. For instance, Lateef *et al*. [95] developed a nanozeolite-based soil amendment for enhancing soil water retention and nutrient holding capacity. Nanozeolites are aluminosilicate minerals with a porous structure and high cation exchange capacity, which can adsorb and release water and nutrients in response to plant demand. The nanozeolite amendment increased soil water content by 20% and reduced nutrient leaching by 40% compared to unamended soil, while improving the growth and yield of tomatoreduced nutrient leaching by 40% compared to unamended soil, while improving the growth and yield of tomato plants by 25%.

In another study, Palmqvist *et al*. [96] developed a nanocellulose-based hydrogel for soil moisture retention and plant growth promotion. Nanocellulose is a biodegradable and renewable nanomaterial derived from plant biomass, which can form a highly porous and absorbent network when cross-linked into a hydrogel. The nanocellulose hydrogel increased soil water holding capacity by 50% and reduced water evaporation by 30% compared to untreated soil, while providing a favorable microenvironment for root growth and microbial activity. The hydrogel amendment also increased the biomass and nitrogen fixation of soybean plants by 40% and 60%, respectively, under drought stress conditions.

Despite these promising results, the application of nanofertilizers and nano-enabled soil amendments still faces several challenges and uncertainties. One major concern is the potential toxicity and ecotoxicity of nanomaterials to plants, soil organisms, and human health [97]. Some studies have reported adverse effects of certain nanomaterials, such as carbon nanotubes and metal oxide nanoparticles, on seed germination, root elongation, and microbial diversity, depending on their concentration, size, and surface properties [98]. Therefore, it is crucial to conduct comprehensive risk assessment and safety testing of nanomaterials before their widespread use in agriculture.

Another challenge is the scalability and cost-effectiveness of nanofertilizer production and application. Most nanofertilizers are currently synthesized using complex and expensive methods, such as chemical vapor deposition, sol-gel processing, or electrospinning, which may limit their commercial viability and adoption by farmers [99]. Moreover, the optimal dosage, frequency, and method of nanofertilizer application may vary depending on the crop species, growth stage, soil type, and environmental conditions, requiring site-specific management and precision agriculture techniques [100].

To address these challenges, future research should focus on developing green and sustainable synthesis methods for nanofertilizers, using biobased and biodegradable materials, such as plant extracts, algae, or agricultural waste [101]. The safety and efficacy of nanofertilizers should be evaluated using standardized protocols and multi-trophic ecotoxicity tests, considering their fate, transport, and transformation in the agroecosystem [102]. The synergistic effects of nanofertilizers with other precision agriculture technologies, such as nanosensors, remote sensing, and variable rate application, should also be explored to optimize their performance and minimize their environmental footprint [103].

6. Integration of Nanosensors with Wireless Networks and Data Analytics for Precision Agriculture

The integration of nanosensors with wireless sensor networks (WSNs) and data analytics platforms is essential for realizing the full potential of nanotechnology-enabled precision agriculture [104]. WSNs are a key component of the Internet of Things (IoT) paradigm, which enables the interconnection and communication of smart devices and objects over the internet [105]. In the context of precision agriculture, WSNs can provide real-time and spatially distributed monitoring of soil, crop, and environmental parameters, using a network of wireless nodes equipped with nanosensors and other sensing devices [106].

The architecture of a typical WSN for precision agriculture consists of three main layers [107]:

1. Sensing layer: This layer includes the nanosensors and other sensing devices that collect data on soil moisture, temperature, pH, nutrient levels, crop growth, and other relevant variables. The nanosensors are usually integrated with wireless transceiver modules, microcontrollers, and power sources to form autonomous and self-powered sensing nodes.

2. Communication layer: This layer enables the wireless transmission of sensor data from the sensing nodes to a base station or gateway, using various communication protocols such as ZigBee, LoRa, or Wi-Fi. The base station may also communicate with other base stations or remote servers via a backhaul network, such as cellular or satellite.

3. Application layer: This layer involves the storage, processing, analysis, and visualization of sensor data using cloud computing, big data analytics, and machine learning techniques. The analyzed data can be used to generate actionable insights, recommendations, and alerts for farmers, such as optimal irrigation schedules, fertilizer application rates, or pest control measures.

Several studies have demonstrated the integration of nanosensors with WSNs for precision agriculture applications. For example, Cao *et al*. [108] developed a WSN system for real-time monitoring of soil moisture and nitrogen levels using carbon nanotube-based capacitive sensors. The nanosensors were fabricated by depositing a layer of multi-walled carbon nanotubes (MWCNTs) on a flexible polyimide substrate, followed by encapsulation with a moisture-sensitive polymer. The nanosensors had a high sensitivity of 0.2 pF/%RH and a low detection limit of 0.1% for soil moisture, and a sensitivity of 5.2 pF/mM and a detection limit of 0.5 mM for soil nitrate. The nanosensors were integrated with a ZigBee-based wireless transceiver module and a solar-powered battery, forming a self-sustained sensing node. A network of 20 sensing nodes was deployed in a wheat field to monitor the spatio-temporal variability of soil moisture and nitrogen levels. The sensor data were transmitted to a base station and then to a cloud server for data storage, processing, and visualization. The WSN system provided valuable information for optimizing irrigation and fertilization management, resulting in a 15% increase in wheat yield and a 20% reduction in water and fertilizer use compared to conventional practices.

In another study, Kim *et al*. [109] developed a WSN system for monitoring soil pH and nutrient levels using graphene-based potentiometric sensors. The nanosensors were fabricated by depositing a layer of reduced graphene oxide (rGO) on a screen-printed carbon electrode, followed by functionalization with ion-selective membranes for pH, potassium, and nitrate detection. The nanosensors had a wide linear range of 3-9 for pH, 0.1-10 mM for potassium, and 0.5-50 mM for nitrate, with a response time of less than 10 s. The nanosensors were integrated with a LoRa-based wireless transceiver module and a rechargeable battery, forming a low-power and long-range sensing node. A network of 10 sensing nodes was deployed in a rice paddy field to monitor the spatial and temporal dynamics of soil pH and nutrient levels. The sensor data were transmitted to a LoRa gateway and then to a web server for data analytics and visualization. The WSN system provided real-time information for precision fertilization and liming management, resulting in a 10% increase in rice yield and a 15% reduction in fertilizer use compared to uniform application.

The integration of nanosensors with WSNs can generate large volumes and varieties of data, which require advanced data analytics and machine learning techniques to extract meaningful insights and support decision-making [110]. Some common data analytics techniques for precision agriculture include:

1. Descriptive analytics: This involves summarizing and visualizing sensor data using statistical methods and graphical tools, such as histograms, scatter plots, and heat maps, to identify patterns, trends, and outliers in soil and crop parameters [111].
2. Diagnostic analytics: This involves analyzing sensor data to identify the causes and factors influencing soil and crop variability, using techniques such as correlation analysis, principal component analysis, and clustering [112].
3. Predictive analytics: This involves using sensor data to build models that can predict future soil and crop conditions, such as yield, quality, and stress, using techniques such as regression analysis, time series analysis, and machine learning algorithms [113].
4. Prescriptive analytics: This involves using sensor data and predictive models to generate site-specific recommendations and optimized management strategies, such as variable rate application of inputs, precision irrigation, and targeted pest control [114].

Machine learning, in particular, has shown great potential for leveraging the full value of nanosensor data in precision agriculture [115]. Machine learning algorithms can automatically learn patterns and relationships from large datasets, without being explicitly programmed, and can improve their performance over time with new data [116]. Some common machine learning algorithms for precision agriculture include:

1. Support vector machines (SVM): These are supervised learning algorithms that can classify and predict soil and crop parameters based on input features, by finding the optimal hyperplane that separates different classes in a high-dimensional space [117].
2. Random forests (RF): These are ensemble learning algorithms that combine multiple decision trees to improve the accuracy and robustness of predictions, by averaging or voting the outputs of individual trees [118].
3. Artificial neural networks (ANN): These are biologically inspired algorithms that can model complex and nonlinear relationships between input and output variables, by simulating the structure and function of the human brain [119].
4. Deep learning (DL): These are advanced neural network algorithms that can learn hierarchical and abstract features from raw data, using multiple layers of nodes and connections, and can outperform traditional machine learning algorithms in tasks such as image recognition, speech recognition, and natural language processing [120].

Several studies have applied machine learning algorithms to nanosensor data for precision agriculture. For example, Mohammadi *et al*. [121] developed an ANN model for predicting soil moisture content based on data from carbon nanotube-based capacitive sensors. The model was trained and tested using data from a network of 20 sensors deployed in a maize field, with 70% of the data used for training and 30% for testing. The model had an input layer with four neurons (corresponding to the four sensors), a hidden layer with eight neurons, and an output layer with one neuron (corresponding to the predicted soil moisture). The model was optimized using the Levenberg-Marquardt algorithm and evaluated using the mean squared error (MSE) and coefficient of determination (R^2^) metrics. The results showed that the ANN model could predict soil moisture with an MSE of 0.02 and an R^2^ of 0.95, indicating a high accuracy and goodness of fit. The model was then used to generate a soil moisture map of the field, which could guide variable rate irrigation decisions.

In another study, Meena *et al*. [122] developed an SVM model for predicting soil nutrient levels based on data from graphene-based electrochemical sensors. The model was trained and tested using data from a network of 50 sensors deployed in a sugarcane field, with 80% of the data used for training and 20% for testing. The model had an input layer with six features (corresponding to the sensor readings for pH, potassium, nitrogen, phosphorus, sulfur, and carbon), a kernel layer with a radial basis function (RBF), and an output layer with six classes (corresponding to the nutrient deficiency levels). The model was optimized using the grid search method and evaluated using the accuracy, precision, recall, and F1-score metrics. The results showed that the SVM model could predict nutrient deficiency levels with an accuracy of 92%, a precision of 0.91, a recall of 0.93, and an F1-score of 0.92, indicating a high performance and reliability. The model was then used to generate a nutrient deficiency map of the field, which could guide precision fertilization decisions.

7. Challenges and Opportunities for Large-Scale Deployment of Nanotechnology-Enabled Soil Monitoring

Despite the significant potential of nanotechnology-enabled soil monitoring for precision agriculture, there are several challenges and barriers that need to be addressed for its large-scale deployment and adoption. These include:

7.1. Technical Challenges

1. Scalability and cost: The fabrication of nanosensors often involves complex and expensive processes, such as lithography, chemical vapor deposition, or atomic layer deposition, which may limit their mass production and affordability [123]. The cost of nanosensors needs to be reduced to a level that is economically viable for farmers, considering the large number of sensors required per hectare and the need for periodic replacement.

2. Reliability and durability: Nanosensors are exposed to harsh and variable soil conditions, such as high temperature, humidity, salinity, and acidity, which can affect their performance and lifetime [124]. The sensors need to be robust and stable enough to provide accurate and consistent measurements over extended periods, without significant drift or degradation.

3. Selectivity and interference: Soil is a complex and heterogeneous medium, containing a wide range of chemical and biological species that can interfere with the target analytes and cause false readings [125]. Nanosensors need to be highly selective and specific to the desired parameters, with minimal cross-sensitivity to other soil constituents.

4. Power and communication: Nanosensors require a reliable and sustainable power source to operate continuously in the field, as well as a wireless communication module to transmit data to a base station or cloud server [126]. The power consumption of nanosensors needs to be minimized to extend their battery life, while the communication range and bandwidth need to be optimized to cover large areas and handle high data rates.

7.2. Environmental and Safety Challenges

1. Ecotoxicity and biodegradability: The release and accumulation of nanosensors and nanomaterials in the soil may pose potential risks to soil ecosystems and food safety, depending on their composition, size, shape, and surface properties [127]. Nanosensors need to be designed with biocompatible and biodegradable materials, such as biopolymers or green synthesized nanoparticles, to minimize their environmental impact and ensure their safe disposal.

2. Regulation and standards: The use of nanosensors in agriculture is subject to various regulations and standards, related to food safety, environmental protection, and occupational health [128]. There is a need for clear and harmonized guidelines and protocols for the testing, labeling, and monitoring of nanosensors, to ensure their compliance with relevant laws and standards.

3. Public perception and acceptance: The public may have concerns and misconceptions about the safety and benefits of nanotechnology in agriculture, which can hinder its adoption and commercialization [129]. There is a need for effective communication and engagement strategies to raise awareness, build trust, and address the societal and ethical implications of nanosensors, in collaboration with stakeholders such as farmers, consumers, and policymakers.

7.3. Socio-Economic and Institutional Challenges

1. Cost-benefit analysis: The adoption of nanosensors in precision agriculture depends on their economic feasibility and return on investment for farmers, considering the costs of hardware, software, and services, as well as the potential benefits in terms of increased yield, quality, and resource efficiency [130]. There is a need for comprehensive cost-benefit analyses and business models that demonstrate the value proposition of nanosensors, based on real-world case studies and pilot projects.

2. Skill and knowledge gaps: The use of nanosensors in precision agriculture requires a certain level of technical and digital skills, as well as agronomic knowledge, which may be lacking among some farmers and extension agents [131]. There is a need for capacity building and training programs that can equip farmers with the necessary competencies and tools to effectively use and interpret nanosensor data, as well as access to advisory and support services.

3. Institutional and policy support: The large-scale deployment of nanosensors in precision agriculture requires an enabling institutional and policy environment, that can provide incentives, resources, and coordination for research, development, and innovation [132]. There is a need for strategic partnerships and collaborations between academia, industry, government, and civil society, to create a conducive ecosystem for nanotechnology-enabled precision agriculture, aligned with sustainable development goals and priorities.

Despite these challenges, there are also significant opportunities and drivers for the large-scale deployment of nanotechnology-enabled soil monitoring in precision agriculture. These include:

1. Increasing demand for food and nutrition security: The global population is projected to reach 9.7 billion by 2050, which will require a 70% increase in food production from current levels [133]. Precision agriculture, enabled by nanosensors and other technologies, can help to meet

this demand by optimizing crop yield, quality, and nutritional value, while minimizing resource use and environmental impact.

2. Advancing technology and innovation: The rapid progress and convergence of nanotechnology, biotechnology, information technology, and cognitive science (NBIC) is creating new opportunities and synergies for precision agriculture [134]. The integration of nanosensors with other emerging technologies, such as robotics, drones, satellites, and blockchain, can enable more intelligent, autonomous, and transparent farming systems.

3. Growing awareness and support for sustainable agriculture: There is a growing recognition and demand for sustainable and resilient agriculture practices, that can balance food production with environmental stewardship and social well-being [135]. Nanotechnology-enabled precision agriculture can contribute to sustainable intensification, by reducing the use of agro-chemicals, water, and energy, as well as enhancing soil health, biodiversity, and carbon sequestration.

4. Increasing investment and collaboration in agri-nanotechnology: There is a growing interest and investment in the application of nanotechnology in agriculture, from both public and private sectors, as well as international organizations and foundations [136]. For example, the European Union has launched several research and innovation programs, such as Horizon 2020 and Food 2030, that support the development and deployment of nanotechnology-enabled solutions for sustainable and productive agriculture.

5. Supportive policies and regulations for precision agriculture: Several countries and regions have developed policies and programs to promote the adoption and diffusion of precision agriculture technologies, including nanosensors, as part of their agricultural modernization and digitalization strategies Supportive policies and regulations for precision agriculture: Several countries and regions have developed policies and programs to promote the adoption and diffusion of precision agriculture technologies, including nanosensors, as part of their agricultural modernization and digitalization strategies [137]. For example, the United States has implemented the Precision Agriculture Connectivity Act of 2018, which aims to expand broadband internet access in rural areas to enable precision agriculture technologies and services [138]. The European Union has also launched the European Green Deal and the Farm to Fork Strategy, which support the transition to sustainable and digital agriculture, including the use of precision farming technologies and data-driven decision making [139].

To realize these opportunities and overcome the challenges, there is a need for a multi-stakeholder and interdisciplinary approach to the development and deployment of nanotechnology-enabled soil monitoring in precision agriculture. **This approach should involve:**

1. Collaborative research and innovation: Fostering collaboration and knowledge exchange between researchers, engineers, agronomists, farmers, and other stakeholders, to co-design and co-develop nanosensors and precision agriculture solutions that are technically feasible, economically viable, environmentally sustainable, and socially acceptable [140].

2. Responsible and inclusive innovation: Integrating responsible research and innovation (RRI) principles and practices, such as anticipation, reflexivity, inclusiveness, and responsiveness, into the development and governance of nanosensors and precision agriculture, to ensure their alignment with societal values, needs, and expectations [141].

3. Capacity building and knowledge transfer: Providing education, training, and extension services to farmers, students, and professionals, to build their capacity and skills in using and interpreting nanosensor data, as well as adopting and adapting precision agriculture practices to their local contexts and needs [142].

4. Enabling policies and regulations: Developing and implementing policies and regulations that create an enabling environment for the development and adoption of nanosensors and precision agriculture, such as investment in research and infrastructure, subsidies and incentives for farmers, data privacy and security, and intellectual property rights [143].

5. Multi-stakeholder dialogue and engagement: Establishing and facilitating multi-stakeholder platforms and networks, such as innovation hubs, living labs, and public-private partnerships, to engage and empower diverse actors in the co-creation and co-implementation of nanotechnology-enabled precision agriculture, as well as in the anticipation and mitigation of potential risks and unintended consequences [144].

8. Future Perspectives

Nanotechnology-enabled soil monitoring has the potential to revolutionize precision agriculture by providing real-time, high-resolution, and actionable data on soil properties and processes, which can inform site-specific and timely management decisions. This review has presented an overview of the current state-of-the-art and future prospects of nanotechnology-based sensors and networks for soil monitoring, including their principles, applications, challenges, and opportunities.

The unique properties and functionalities of nanomaterials, such as high surface area, reactivity, and specificity, have enabled the development of novel and advanced sensors for measuring various soil parameters, such as moisture, nutrients, pH, organic matter, and microbial activity. Carbon nanomaterials, metal and metal oxide nanoparticles, and nano-biosensors have shown promising results in terms of sensitivity, selectivity, speed, and stability, compared to conventional soil sensors. Nanotechnology has also enabled the development of smart fertilizers and soil amendments, which can enhance nutrient use efficiency, reduce environmental impacts, and improve soil health.

The integration of nanosensors with wireless sensor networks and data analytics has the potential to enable real-time, site-specific, and data-driven precision agriculture. Machine learning algorithms, such as artificial neural networks and support vector machines, have been applied to nanosensor data to predict soil and crop parameters, as well as to generate management recommendations and decisions. The large-scale deployment of nanotechnology-enabled soil monitoring can contribute to sustainable intensification of agriculture, by optimizing resource use, minimizing environmental impacts, and enhancing food security and nutrition.However, there are also several technical, environmental, safety, socio-economic, and institutional challenges that need to be addressed for the responsible and effective development and adoption of nanotechnology-enabled soil monitoring in precision agriculture. These include issues related to scalability, reliability, selectivity, power, ecotoxicity, biodegradability, regulation, public perception, cost-benefit, skills, and policies. To overcome these challenges and realize the opportunities, there is a need for collaborative, inclusive, and responsible research and innovation, as well as enabling policies, regulations, and multi-stakeholder engagement.

Future research and development in nanotechnology-enabled soil monitoring should focus on:

1. Developing low-cost, reliable, and biodegradable nanosensors and nanomaterials, using green and sustainable synthesis methods and biobased feedstocks [145].

2. Integrating nanosensors with other emerging technologies, such as printed electronics, flexible electronics, and energy harvesting, to enable self-powered, wearable, and disposable soil sensing devices [146].

3. Advancing data analytics and machine learning algorithms, such as deep learning and transfer learning, to extract more insights and value from nanosensor data, as well as to enable real-time and adaptive decision support systems [147].

4. Conducting comprehensive and systematic assessments of the environmental, health, and safety risks of nanosensors and nanomaterials, using standardized and validated methods, as well as developing guidelines and best practices for their safe and responsible use [148].

5. Engaging and empowering farmers, consumers, and other stakeholders in the co-design, co-development, and co-implementation of nanotechnology-enabled precision agriculture, using participatory and transdisciplinary approaches, such as living labs, citizen science, and responsible research and innovation [149].

6. Developing and implementing enabling policies, regulations, and incentives, such as research funding, tax credits, extension services, and data governance frameworks, to support the development and adoption of nanotechnology-enabled precision agriculture, aligned with sustainable development goals and agroecological principles [150].

Table 8. Indian case studies of nanotechnology-enabled soil monitoring

Location	**Crop**	**Nanosensor**	**Parameter**	**Benefit**	**Reference**
Punjab	Rice, wheat	Graphene oxide	Salinity	15% yield increase, 25% salt reduction	[156]
Maharashtra	Pomegranate	Zinc oxide	Moisture, nutrients	30% yield increase, 20% input saving	[157]
Tamil Nadu	Sugarcane	Carbon dots	Organic carbon	20% yield increase, 30% C sequestration	[158]
Gujarat	Cotton	Silicon nanowires	Sodicity	25% yield increase, 20% Na reduction	[159]
Uttar Pradesh	Mango	Gold NPs	Microbial activity	15% yield increase, 25% biodiversity increase	[160]

Table 9. Challenges and opportunities for nanotechnology-enabled soil monitoring

Challenge	**Opportunity**
High cost and complexity of nanosensor fabrication	Low-cost and scalable manufacturing methods (e.g. printing, self-assembly)
Limited stability and durability in harsh soil	Robust encapsulation and functionalization techniques

conditions	(e.g. polymers, biomolecules)
Potential toxicity and environmental impact of nanomaterials	Biodegradable and biocompatible nanomaterials (e.g. biopolymers, green synthesis)
Lack of standards and regulations for nanofertilizers and nanosensors	Collaborative development of guidelines and best practices by stakeholders
Skill and knowledge gaps among farmers and extension agents	Capacity building and training programs on precision agriculture and nanotechnology

Table 10. Research priorities and future directions for nanotechnology-enabled soil monitoring

Research area	**Priority**
Low-cost and biodegradable nanomaterials and nanosensors	High
Integration of nanosensors with IoT, robotics, and remote sensing	High
Advanced data analytics and decision support systems for precision agriculture	High
Environmental and health risk assessment of nanomaterials in agroecosystems	High
Participatory and transdisciplinary approaches for technology co-development and adoption	Medium
Enabling policies and regulations for responsible and sustainable nanotechnology in agriculture	Medium

Conclusion

Nanotechnology-enabled soil monitoring has the potential to transform precision agriculture and contribute to a more sustainable, resilient, and productive food system. However, realizing this potential will require a concerted and collaborative effort from all stakeholders, including researchers, farmers, policymakers, industry, and civil society. By working together and leveraging the power of nanotechnology and data analytics, we can develop and deploy innovative and responsible solutions for soil monitoring and management, which can benefit both people and the planet.

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