

# Nanotechnology-Based Detection and Remediation for the Environment, Food and Agriculture



# Nanotechnology-Based Detection and Remediation for the Environment, Food and Agriculture

Edited by

Monika Kundu, Shiv Prasad,  
Ananta Vashisth and Prameela Krishnan

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for the Environment, Food and Agriculture

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and Prameela Krishnan

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## PREFACE

The nexus of environment, food, and agriculture is increasingly strained by escalating global demands and the proliferation of contaminants that threaten human health and ecosystems. In this context, nanotechnology has emerged as a transformative force, offering unprecedented capabilities in detection and remediation. *Nanotechnology-Based Detection and Remediation for the Environment, Food, and Agriculture* is a testament to the profound potential of nanoscale science in addressing these critical challenges.

This book serves as a comprehensive guide for researchers, practitioners, and policymakers seeking to harness nanotechnology to detect contaminants, enhance food safety, and mitigate environmental pollution. It delves into the design, development, and application of nanomaterials and nanodevices, highlighting their precision, sensitivity, and sustainability. From nanosensors capable of detecting trace contaminants in water and soil to nano-enabled strategies for remediating pollutants and ensuring agricultural productivity, this volume bridges cutting-edge science with practical solutions.

The chapters in this book are authored by experts from diverse disciplines, offering interdisciplinary insights and real-world case studies. Each section is crafted to provide both foundational knowledge and an exploration of emerging trends, making it an invaluable resource for both novices and seasoned professionals.

As the world grapples with complex issues like climate change, food security, and environmental degradation, the need for innovative approaches has never been more urgent. It is my hope that this book will inspire novel applications, foster collaboration, and accelerate the adoption of nanotechnology to create a sustainable future for generations to come.

Let us explore the boundless possibilities of nanotechnology in forging a cleaner, safer, and more resilient world.

Monika Kundu  
Shiv Prasad  
Prameela Krishnan  
Ananta Vashisth

April 2025

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## ABOUT THE BOOK

The 21<sup>st</sup> century has witnessed remarkable advancements in science and technology, with nanotechnology emerging as a transformative force. Its potential to address some of the most pressing global challenges—particularly in environmental sustainability, food security, and agricultural productivity—has captured the attention of researchers and policymakers worldwide. The ability to engineer materials at the nanoscale has opened new avenues for detection and remediation strategies, enabling precision, efficiency, and sustainability like never before.

This book, *Nanotechnology-Based Detection and Remediation for the Environment, Food, and Agriculture*, delves into the innovative applications of nanotechnology in these critical domains. The environmental section explores how nanotechnology can monitor, detect, and mitigate pollution through advanced nanomaterials and sensors, offering solutions for water purification, air quality improvement, and soil remediation. In the realm of food science, nanotechnology's role in ensuring safety and quality through intelligent packaging, real-time contaminant detection, and extending product shelf life is examined. Similarly, the agricultural sector benefits from nanotechnology in precision farming, pest control, nutrient delivery, and crop health monitoring, ensuring sustainable practices and higher yields. A unique feature of nanotechnology is its ability to integrate detection and remediation seamlessly. Biosensors, nano-adsorbents, and nanostructured materials not only identify contaminants or inefficiencies but also provide tools for their resolution. This synergy is particularly critical in addressing the interlinked challenges of environmental degradation, food safety, and agricultural productivity. The content presented here is a result of interdisciplinary collaboration, bridging material science, biology, chemistry, and engineering. It highlights cutting-edge research, practical applications, and future prospects, aiming to inspire scientists, students, and practitioners to harness the potential of nanotechnology for a sustainable future.

We hope this work provides valuable insights and contributes to ongoing efforts to leverage technology for the betterment of society and the planet.

A brief summary of chapter in the book is presented here.

**Chapter 1 and chapter 2** provides the overview of the nanotechnology use and applications in food, agriculture and environment. The detailed introduction of natural, incidental and engineered nanomaterials has been discussed for eco-friendly and sustainable agriculture. Chapters reviews past and present description of nanomaterials, their sources and production.

**Chapter 3 to chapter 6** reviews methodology, procedures and techniques for the characterization of nanomaterials along with instrumental description for nanomaterials fabrication and biosensing studies (chapter 3 and chapter 5). Chapter 4 discusses on green nanotechnology, various phytochemicals resources, factors affecting green synthesis, present and future application areas of green nanomaterials. Chapter 6 especially focusses on sensitive and specific detection methods and techniques using nano-sensors. Various fabrication approaches and applications of nanosensors have been thoroughly reviewed.

**Chapter 7 to chapter 10** provides information on environmental and remediation techniques of nanotechnology including engineered nanomaterials (ENMs) approaches for a clean and green environment, Importance of designing ENMs for environmental safety, Risk assessment models, various case studies, Future directions and challenges in nanomaterials design. Detailed reviews have been presented on nanotoxicity, its detection, exposure routes, impact and hazard management.

**Chapter 11 to chapter 13** provides detailed studies on applications of nanotechnology in food and feed sector. Nanomaterials interventions in food processing, value additions, food production, food packaging, in aquaculture nutrition, novel feed development incorporating nanomaterials, seafood packaging, nanobubble technology, toxicity to fish and shellfish have been discussed in detail.

**Chapter 14 to chapter 18** provides information on agriculture, sustainability contribution of nanotechnology. In these chapters detailed discussion have been included on comparison of nanofertilizer standards in commercial agriculture including regulatory framework and standards across countries and regions, nanoinsecticides for crop protection, nanoformulations developed, along with active ingredients against different insect pests, nanotechnology advancements in agriculture with emerging frontiers and applications, specific case study on zinc oxide nanoparticles as a novel approach to enhance zinc bioavailability in rice have been discussed in detail. Also various advancements in nanomaterial fabrication, characterization methods, sensing techniques for climate resilient and sustainable agriculture have been covered.

# CHAPTER 1

## OVERVIEW OF NANOTECHNOLOGY AND BIOSENSORS IN AGRICULTURE

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### **Abstract**

Nanotechnology and biosensors are revolutionizing the agricultural sector by introducing precision tools and innovative solutions to enhance productivity and sustainability. The application of nanotechnology enables the development of nano-fertilizers and nano-pesticides that offer targeted delivery and controlled release, improving the efficiency of nutrient uptake and pest control while minimizing environmental impact. On the other hand, biosensors provide real-time monitoring of soil health, water quality, and crop conditions, enabling farmers to make informed decisions for optimal resource management. These susceptible devices can accurately detect pathogens, nutrient levels, and other stress factors, aiding in early disease detection and proactive treatment. Integrating these technologies promotes sustainable farming practices, reducing chemical runoff and supporting better yield management. As a result, the combination of nanotechnology and biosensors offers promising solutions to meet the growing global food demand while addressing ecological challenges and improving agricultural resilience.

**Keywords:** Nanotechnology, Biosensors, Green methods, Nanotoxicity, Applications

## Introduction

Nanotechnology and biosensors are revolutionizing modern agriculture, addressing the critical need for increased productivity and sustainability in a world facing climate change, population growth, and diminishing natural resources. Nanotechnology refers to the manipulation of materials at the nanoscale (1-100 nanometers), where unique physical and chemical properties can be leveraged to develop advanced agricultural solutions [Soni, Dogra, Sharma, Thakur, et al., 2024, 1–34]. On the other hand, biosensors are analytical devices that use a biological recognition element and a transducer to detect and measure biological or chemical processes, providing real-time data crucial for precision farming [Gangwar, 2024, 1–25]. Nanotechnology offers numerous applications that significantly impact agricultural practices. Nano-fertilizers, for instance, deliver nutrients in a controlled release manner, ensuring plants absorb them more efficiently and reducing environmental waste. This targeted approach minimizes runoff and enhances soil health, promoting sustainable practices [Yadav, Yadav, & Abd-Elsalam, 2023b, 296–336]. Nano-pesticides also provide targeted pest control, reducing the quantity of active chemicals required and mitigating the impact on non-target organisms [Li, Chen, Xu, Lynch, et al., 2023, 108051]. Using nanomaterials such as nano-silica and silver nanoparticles helps enhance plant protection, offering antimicrobial properties that guard crops against diseases. Biosensors complement nanotechnology by providing precise, on-the-spot monitoring of various agricultural parameters. They can detect nutrient levels, soil pH, moisture content, and the presence of pathogens or pests, enabling farmers to make informed decisions quickly. For example, enzyme-based and DNA-based biosensors can identify specific plant pathogens at an early stage, allowing farmers to act before widespread damage occurs [Khan, Burciu, Filipe, Li, et al., 2021, 13943–13969; Melo, Neto, Dari, Fernandes, et al., 2024, 130817].

Water quality assessment through biosensors ensures that irrigation is free from harmful contaminants, safeguarding crops and the surrounding environment. Combining nanotechnology and biosensors creates powerful tools that enhance the accuracy and efficiency of agricultural practices. Nanomaterials like carbon nanotubes and gold nanoparticles are integrated into biosensors to amplify signals, improving their sensitivity and detection limits. This synergy allows for developing multifunctional sensors capable

of monitoring multiple environmental factors simultaneously [Alim, Vejayan, Yusoff, & Kafi, 2018, 125–136]. Such innovations facilitate precision agriculture, where water, fertilizers, and pesticides are applied optimally, reducing costs and environmental impact while boosting crop yields. However, the adoption of these technologies comes with challenges.

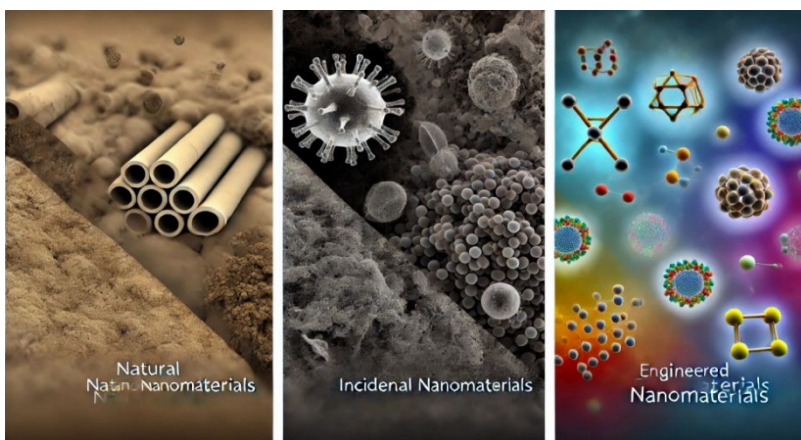
High initial costs and the need for specialized knowledge can be barriers for small-scale farmers, potentially limiting widespread use. Additionally, there are concerns about nanomaterials' long-term environmental and health effects, necessitating thorough research and regulation to ensure safety. Despite these challenges, advancements in nanotechnology and biosensor development continue to pave the way for more sustainable and resilient agricultural practices. The future may see the integration of these technologies with digital tools, such as IoT and AI, providing farmers with real-time data analysis and automated decision-making capabilities. This evolution has the potential to transform agriculture into a highly efficient, adaptive, and environmentally friendly industry capable of meeting the growing demands of the global population [Ullah, Adhikari, Su, Palmieri, et al., 2024]. Nanotechnology and biosensors are expected to play transformative roles in the agriculture and food industries in the future, enhancing sustainability, productivity, and safety.

Nanotechnology will enable the development of ultra-precise nano-fertilizers and nano-pesticides that improve nutrient absorption and targeted pest control, reducing waste and environmental impact. Nanoparticles may also be utilized for advanced food packaging that extends shelf life and detects spoilage through embedded sensors. Biosensors will continue to evolve as essential tools for precision agriculture, providing real-time monitoring of soil health, nutrient levels, and crop conditions to optimize resource use. Additionally, biosensors will be critical for food safety and can quickly detect contaminants, pathogens, and chemical residues, ensuring a safer supply chain from farm to table. As these technologies integrate with IoT and AI, they promise more data-driven decision-making, fostering efficient and sustainable food production and distribution systems.

### **Natural, incidental, and engineered nanomaterials**

Nanomaterials are classified into three primary types: natural, incidental, and engineered, each with distinct origins, synthesis methods, and applications in agriculture, food, soil, and water management. Natural nanomaterials are found in the environment, including volcanic ash, clays, and organic matter produced through biological processes (Fig 1-1). These naturally occurring nanoparticles can influence soil fertility and nutrient

cycling. Incidental nanomaterials arise as by-products of industrial processes such as combustion and mining, affecting air, water, and soil quality. Managing these nanoparticles involves mitigating their potential negative environmental impact through careful monitoring and remediation strategies. Engineered nanomaterials, on the other hand, are synthesized intentionally for specific applications and exhibit controlled properties tailored for particular functions. The synthesis methods for engineered nanomaterials include physical, chemical, and biological approaches. Physical processes, like high-energy ball milling and laser ablation, generate nanomaterials through mechanical force or laser energy.



**Fig. 1-1** Different types of nanomaterials

Chemical methods involve precipitation, sol-gel processes, and chemical vapor deposition to create nanoparticles with desired characteristics. Biological synthesis employs microorganisms, plants, or enzymes to produce more environmentally friendly nanoparticles, harnessing natural processes for nanoparticle formation [Barhoum, García-Betancourt, Jeevanandam, Hussien, et al., 2022, 177]. In agriculture, engineered nanomaterials have applications as nano-fertilizers and nano-pesticides, enhancing nutrient delivery and pest control while reducing environmental damage. These nanomaterials increase the efficiency of agrochemical use, ensuring that resources are optimized for plant absorption [Adisa, Pullagurala, Peralta-Videa, Dimkpa, et al., 2019, 2002–2030].

In the food industry, nanomaterials are used to improve food packaging by incorporating nanosensors that detect spoilage or contamination, extending shelf life and ensuring safety. Soil applications include

nanomaterials for soil remediation, where substances like nano-iron are used to neutralize pollutants and enhance soil health. In water treatment, nanomaterials such as carbon nanotubes and nano-ceramics are employed to remove contaminants, filter out heavy metals, and improve water quality through advanced filtration systems. The versatility and adaptability of natural, incidental, and engineered nanomaterials and innovative synthesis techniques hold vast potential to revolutionize sustainable agricultural practices, food safety, and environmental management.

### **Techniques and methods of nanotechnology for agricultural applications**

The application of nanotechnology in agriculture relies heavily on precise characterization techniques to understand and manipulate nanomaterials for effective use. Characterization techniques such as spectroscopy, electron microscopy, and zeta potential analysis are essential for determining nanomaterials' physical and chemical properties, influencing their behavior and effectiveness in agricultural settings. Spectroscopy techniques are invaluable for analyzing the structural and compositional properties of nanomaterials. Methods like UV-Vis spectroscopy help determine the optical properties of nanoparticles, enabling the study of their size and concentration in a solution. Fourier-transform infrared (FTIR) spectroscopy provides information about the chemical bonds and functional groups on the surface of nanoparticles, which is crucial for understanding how these particles interact with biological and chemical environments in agricultural applications, such as targeted nutrient delivery or pest control.

Raman spectroscopy is also used to study molecular vibrations. It provides insights into nanomaterials' chemical structure and phase, aiding in developing nanostructures tailored for specific agricultural uses. Electron microscopy techniques, such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM), are critical for visualizing nanoparticles' morphology and internal structure. SEM provides high-resolution images of the surface topography, allowing researchers to observe the shape and size distribution of nanoparticles. This is important for determining how these particles interact with plant surfaces or soil components. TEM offers even higher resolution and is used to observe the internal structure of nanoparticles at the atomic level, providing detailed insights into their crystallinity and lattice structure. Such detailed characterization is vital for creating nanoparticles with precise properties for nano-fertilizers or nano-pesticides, enhancing nutrient absorption and pest control efficacy. Zeta potential analysis measures the surface charge of

nanoparticles, indicating their suspension stability. In agricultural applications, the zeta potential helps predict the behaviour of nanoparticles in various media, such as soil or water. A high absolute zeta potential indicates good stability, preventing the accumulation of particles and ensuring consistent distribution in formulations. This property is essential for applications where nanoparticles must remain dispersed to be effective, such as in foliar sprays or soil amendments. Other characterization techniques include dynamic light scattering (DLS), which measures the size distribution of nanoparticles in a colloidal solution and is critical for ensuring that the particles are within the desired size range for specific agricultural functions. X-ray diffraction (XRD) is employed to determine the crystalline structure of nanoparticles, revealing their phase composition and helping identify the most stable and reactive forms of a given nanomaterial. Energy-dispersive X-ray spectroscopy (EDX), often used with SEM, provides elemental analysis of nanoparticles, offering a comprehensive understanding of their composition. Confocal Microscopy is an advanced imaging technique used to obtain high-resolution, three-dimensional images of samples, which is particularly valuable in studying nanomaterials in agricultural applications. Unlike traditional optical microscopy, which captures light from the entire specimen, confocal microscopy utilizes a pinhole to block out-of-focus light, allowing only light from the focal plane to be captured. This results in enhanced image clarity and depth, making it possible to examine structures at the nanoscale level with high precision. In agriculture, confocal microscopy is instrumental in the detailed visualization of the interactions between nanomaterials and plant tissues. For instance, confocal microscopy can track nano-fertilizer uptake by plant roots and leaves, offering insights into how these nanoparticles move within the plant system. This allows researchers to study the distribution of nutrients and identify the optimal size and surface properties for improved absorption and efficiency. Moreover, nanoparticles used in nano-pesticides can be visualized to understand how they interact with pests at the cellular level. The technique enables observing how nanoparticles adhere to insect surfaces or infiltrate plant pathogens, revealing pest control mechanisms. This capability is vital for tailoring nanomaterials to achieve targeted delivery systems, ensuring they are effective in small quantities while minimizing environmental toxicity.

Confocal microscopy also plays a role in studying nanomaterials in soil. It allows for the examination of the behaviour of nanoparticles in complex soil matrices, providing information on how they disperse, interact with soil components, and affect soil microbes. This is crucial for assessing the long-term impact of nanomaterials on soil health and determining their potential

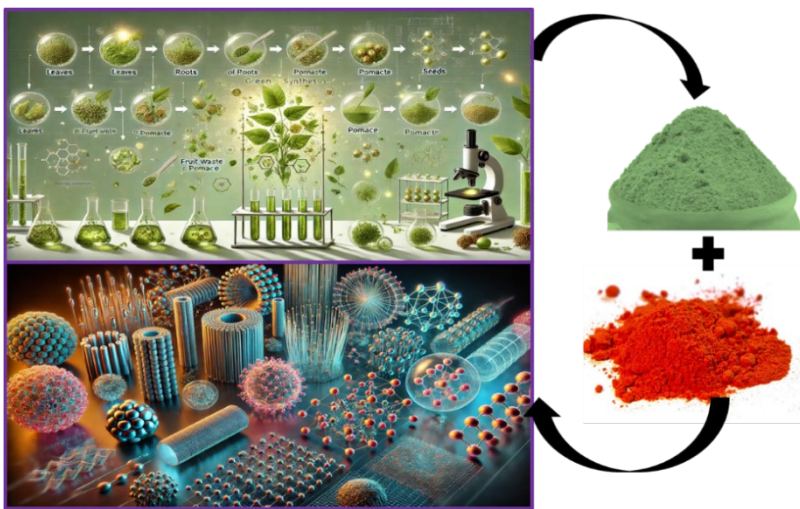
for soil remediation. Confocal microscopy is a powerful tool that offers detailed, high-resolution images critical for understanding nanomaterials' behaviour, interactions, and effectiveness in agricultural settings. By providing visual insights into the dynamics of nano-fertilizers, nano-pesticides, and soil treatment agents, confocal microscopy aids in the design and optimization of nanomaterials for more efficient, sustainable, and environmentally friendly agricultural practices [Jagadeesh, Rangappa, & Siengchin, 2023]. These techniques collectively contribute to the precise characterization of nanomaterials, ensuring their suitability for targeted agricultural applications. For example, nano-fertilizers must have a specific particle size and surface charge to facilitate plants' uptake and controlled release of nutrients. Similarly, nano-pesticides must be engineered for effective delivery and action against pests while minimizing environmental harm. By employing a combination of spectroscopy, electron microscopy, zeta potential analysis, and other advanced techniques, researchers can tailor nanomaterials to enhance crop productivity, improve soil health, and ensure sustainable agricultural practices. These methods form the backbone of the development pipeline, bridging the gap between laboratory research and practical field application, thus advancing the role of nanotechnology in modern agriculture.

## **Green nanotechnology methods and techniques**

Green methods and techniques for synthesizing nanomaterials offer significant advantages in agriculture, promoting sustainability, safety, and efficiency. One of the primary benefits is the reduction of toxic chemicals in the production process. By using natural reducing agents such as plant extracts, microorganisms, and enzymes, these methods minimize the environmental impact and lower the risk of contamination of crops, soil, and water sources [Ahmad, Munir, Zeb, Ullah, et al., 2019 5087–5107]. This approach ensures that nanoparticles are biocompatible and eco-friendly, making them safer for agricultural applications (Fig. 1-2). Energy conservation is another advantage, as many green synthesis methods require lower energy input than traditional chemical synthesis, contributing to reduced carbon emissions and overall environmental impact. The use of green-synthesized nanomaterials also enhances the safety of agricultural products.

Nano-fertilizers and nano-pesticides produced through eco-friendly techniques are more likely to be biodegradable, reducing long-term soil and water pollution. This characteristic helps maintain soil health and prevents the accumulation of potentially harmful residues in the environment,

supporting sustainable farming practices [Yadav, Yadav, & Abd-Elsalam, 2023a, 296–336]. Moreover, green synthesis methods often produce nanoparticles with unique surface properties that improve their effectiveness and targeted action. For instance, biogenic nanoparticles can be engineered to have controlled release properties, ensuring that nutrients or pesticides are delivered efficiently to plants, reducing the amount needed, and minimizing waste. Furthermore, green nanotechnology can improve cost-effectiveness for farmers, as it encourages the use of locally available biological resources for nanoparticle production, decreasing reliance on expensive and toxic chemical reagents. This approach also fosters safer working conditions for farmers and workers who handle these materials, as there is less exposure to hazardous substances.



**Fig. 1-2** Green nanotechnology methods and processes

Ultimately, green nanotechnology methods align with sustainable agricultural goals by enhancing productivity while protecting the environment, promoting a balance between innovation and ecological responsibility. Green nanotechnology is an innovative approach that focuses on the development and application of nanomaterials and nanotechnologies in ways that minimize environmental impact and promote sustainability. The goal of green nanotechnology is to create nanomaterials through environmentally friendly methods that reduce the use of toxic chemicals, conserve energy, and incorporate renewable resources. Essential methods and techniques within this field include the biological or "green"

synthesis of nanoparticles, which leverages natural processes using plant extracts, bacteria, fungi, and enzymes as reducing and stabilizing agents. This method is advantageous because it avoids the harsh chemicals often used in conventional synthesis processes and yields biocompatible nanomaterials suitable for agricultural and medical applications. One of the most widely studied techniques in green nanotechnology is plant-mediated synthesis, where plant extracts containing natural antioxidants and phytochemicals facilitate the reduction of metal salts to form nanoparticles. This method is simple, cost-effective, and scalable, making it an attractive option for large-scale production [Adeyemi, Oriola, Onwudiwe, & Oyediji, 2022, 627]. Microbial synthesis is another approach, harnessing the inherent capabilities of bacteria and fungi to produce nanomaterials [Adeleke, Olowe, Ayilara, Fasusi, et al., 2024]. Microorganisms metabolize metal ions and precipitate them as nanoparticles, which controlling factors like pH, temperature, and nutrient availability can tailor. These biological techniques produce fewer toxic nanomaterials, often resulting in particles with unique surface properties that enhance their application in agriculture and biomedicine. Green nanotechnology also involves adopting energy-efficient processes, such as using solar energy to synthesize nanomaterial and employing eco-friendly solvents like water and bio-based liquids instead of hazardous organic solvents.

Sol-gel processing and supercritical fluid extraction are adapted to minimize energy consumption and reduce waste. Moreover, sustainable nanotechnology design uses biodegradable polymers and plant-based materials to create nano-bio composites that break down naturally without causing environmental harm. Applications of green nanotechnology are vast, particularly in agriculture, where green-synthesized nanoparticles are used to develop safer nano-fertilizers and nano-pesticides that enhance crop productivity while minimizing toxic residue. Green nanomaterials such as biogenic metal nanoparticles and nanocellulose are employed in water treatment to effectively remove pollutants without introducing secondary contamination. Such eco-friendly methods align with global sustainability goals, aiming to reduce the carbon footprint and prevent pollution. Overall, green nanotechnology represents an essential shift toward more responsible and sustainable development in nanotechnology. By focusing on renewable resources, safer synthesis methods, and energy conservation, green nanotechnology contributes to creating a balance between technological advancement and environmental stewardship [Chakrabarty, Hakeem, Mohanta, & Varma, 2022, 3237–3252].

## **Characterization Techniques and Instrumentation for Nanomaterials**

Characterization and instrumentation are critical aspects of nanotechnology, enabling researchers and practitioners to analyze and manipulate nanomaterials for diverse applications accurately. In fields like agriculture, food safety, and environmental science, understanding the properties and behavior of nanoparticles is essential for developing effective and sustainable nanotechnology solutions. Characterization techniques provide insight into structural, chemical, and physical attributes at the nanoscale, influencing their behavior, reactivity, and interactions with biological systems. Instrumentation plays a pivotal role in this, offering the precision required to measure these properties and ensure consistent performance of nanomaterials in various applications [Jagadeesh, Rangappa, & Siengchin, 2024, 122–143; Mourdikoudis, Pallares, & Thanh, 2018, 12871–12934]. Instrumentation in nanotechnology covers a range of techniques that facilitate the detailed study and application of nanomaterials. The scope extends from analyzing particle size and morphology to understanding surface characteristics and chemical composition. The advantages of such precise instrumentation are vast. They include improved control over the synthesis of nanoparticles, better quality assurance, and enhanced reproducibility of results. These benefits are critical when tailoring nanomaterials for targeted functions, such as controlled nutrient delivery in agriculture or pollutant removal in water treatment. Advanced instrumentation enables researchers to optimize the efficacy and safety of nanomaterials, ensuring that they meet the desired specifications for sustainable use [Harish, Ansari, Tewari, Yadav, et al., 2023, 105010].

### **Characterization Techniques**

Characterization techniques in nanotechnology are diverse and specialized, each providing specific insights into nanomaterial properties.

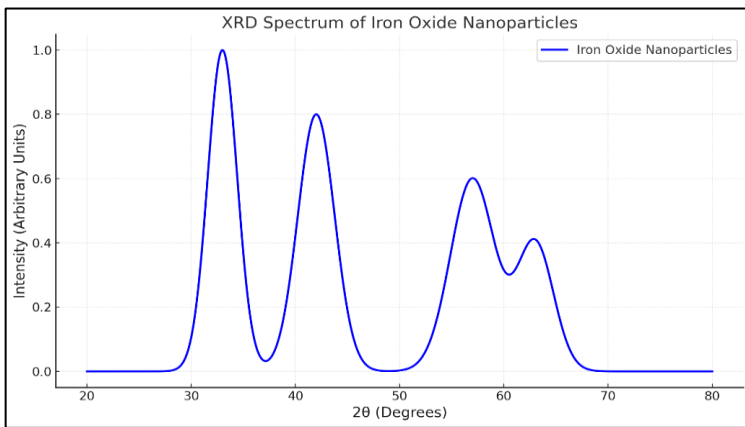
**X-ray Diffraction (XRD):** XRD is a powerful technique used to determine the crystalline structure of nanomaterials. Researchers can identify phase composition and crystallinity by measuring the diffraction patterns of X-rays passing through a sample (Fig. 1-3). This is essential for confirming the purity and stability of nanomaterials used in agriculture for nutrient delivery or pest control.

**Small Angle X-ray Scattering (SAXS):** SAXS offers information about nanoparticle size, shape, and distribution in a suspension. It is beneficial for studying nanoparticles that form complex structures or have

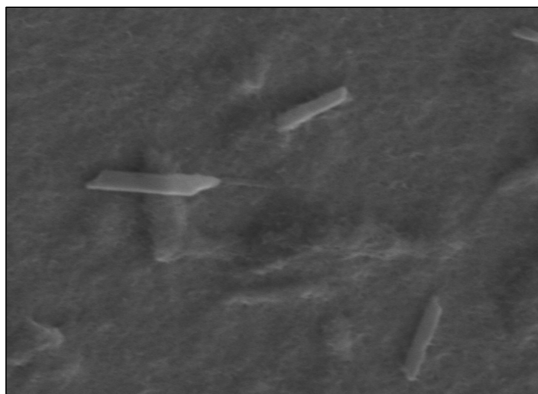
irregular shapes. This method aids in understanding how nanomaterials behave in soil or liquid environments.

**Laser Diffraction Particle Sizing:** Laser diffraction measures the size distribution of nanoparticles. The technique analyzes the pattern of light scattered by particles suspended in a medium. This information is crucial for ensuring uniformity in formulations of nano-fertilizers or pesticides.

**Scanning Electron Microscopy (SEM):** SEM provides high-resolution images of the surface morphology of nanomaterials (Fig. 1-4). It is instrumental in observing nanoparticles' shape and surface texture, allowing for detailed analysis of how they interact with plant surfaces or soil particles.



**Fig. 1-3** Simulated XRD spectrum of iron oxide nanoparticles



**Fig. 1-4** SEM image of multiwalled carbon nanotubes

**High-Resolution Transmission Electron Microscopy (HRTEM):** HRTEM goes beyond conventional TEM by offering atomic-level resolution. This technique is invaluable for studying the internal structure and arrangement of atoms within nanoparticles, helping to verify their integrity and suitability for agricultural applications.

**Atomic Force Microscopy (AFM):** AFM measures nanomaterials' surface topography and mechanical properties. This technique is beneficial for understanding how nanoparticles adhere to different substrates, a key consideration for developing nano-coatings or targeted delivery systems in agriculture.

**Thermogravimetric Analysis (TGA):** TGA measures changes in the weight of a sample as it is heated, providing insights into thermal stability and composition. This method is essential for assessing the durability of nanoparticles in agricultural formulations exposed to varying environmental conditions.

**Dynamic Light Scattering (DLS):** DLS is a technique for measuring the size distribution of nanoparticles in a liquid medium by analyzing fluctuations in light scattering. It is commonly used to monitor the stability and dispersion of nanoparticles in nano-fertilizers or sprays.

**Brunauer-Emmett-Teller (BET):** Surface Area Analysis BET analysis determines the specific surface area of nanoparticles. A higher surface area often correlates with greater reactivity, which is crucial for optimizing the performance of nano-pesticides or soil amendments.

**Fourier Transform Infrared Spectroscopy (FTIR):** FTIR spectroscopy identifies nanoparticle chemical bonds and functional groups. This information is vital for ensuring that nanoparticles interact effectively with plant tissues or degrade safely in the environment.

**Surface Zeta Potential Analysis:** Zeta potential analysis measures the surface charge of nanoparticles, indicating their suspension stability (Fig. 1-5). This is particularly important for developing formulations that remain effective and evenly distributed when applied to crops.

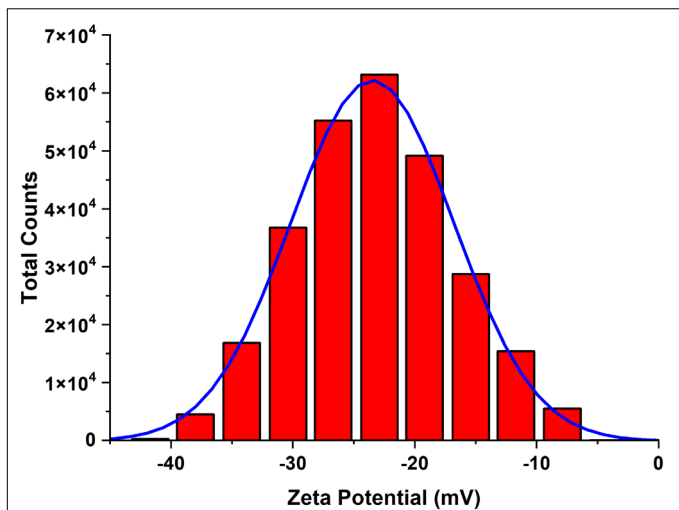


Fig. 1-5 Zeta potential of multiwalled carbon nanotubes

**UV-Vis Spectroscopy:** UV-Vis spectroscopy is used to study the optical properties of nanoparticles. It helps monitor the concentration and uniformity of nanoparticles in solutions, aiding in quality control during production.

**Raman Spectroscopy:** Raman spectroscopy complements FTIR by providing detailed information on molecular vibrations and chemical composition. This technique helps characterize nanoparticle functionalized surfaces intended for specific interactions with soil or plant systems. Combining these techniques enables a comprehensive understanding of nanomaterials, fostering their development for sustainable and precise agricultural applications. Characterization instrumentation for nanomaterials offers significant advantages for advancing their development and application across various fields. These tools enable accurate analysis of nanoparticles' physical, chemical, and structural properties, ensuring a deep understanding of their behavior under different conditions. This is crucial for tailoring nanomaterials to specific uses, such as enhancing nano-fertilizers' efficiency or designing effective nano-pesticides in agriculture. High-resolution techniques like scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide detailed imaging, allowing researchers to observe morphology and internal structures, which aids in fine-tuning synthesis processes for consistent quality.

Instruments like dynamic light scattering (DLS) and zeta potential analysis are vital for assessing particle size distribution and stability, preventing aggregation, and ensuring uniform performance. X-ray diffraction (XRD) and Fourier-transform infrared (FTIR) spectroscopy offer insights into crystalline structure and chemical composition, facilitating customized functionalization for specific applications. These advantages collectively support innovation, improve product reliability, and enhance safety by ensuring that nanomaterials meet high standards, ultimately bridging the gap between laboratory research and practical applications [Jayawardena, Liyanage, Rathnayake, Patel, et al., 2021, 1889–1911].

### **Sensitive and specific detection using Nano-sensors**

Nano-sensors have revolutionized the field of detection and diagnostics by offering empathetic and specific measurement capabilities unparalleled by traditional methods. These tiny, sophisticated devices leverage the unique properties of nanomaterials—such as their high surface area-to-volume ratio, exceptional electrical, optical, and chemical reactivity, and tailored functionalization—to detect minute quantities of substances with great precision. Sensitivity refers to a sensor's ability to detect low levels of a target analyte. At the same time, specificity is its ability to identify a particular substance in the presence of other potentially interfering substances. Nano-sensors excel in both aspects due to the capability of nanomaterials to be engineered at the molecular or atomic level for targeted interactions. For example, metal nanoparticles such as gold and silver are frequently used in sensors due to their strong plasmonic properties, which enhance signal detection in optical sensors [Adam & Dhahi, 2022, 153–173]. In agriculture and food safety, nano-sensors can detect trace amounts of pathogens, pesticides, or nutrient levels in real-time, enabling rapid decision-making to maintain crop health and food quality. Biosensors incorporating nanomaterials like carbon nanotubes, graphene, or quantum dots demonstrate high electrical conductivity and tunable surfaces that can be functionalized with specific biomolecules for targeted binding (Fig. 1-6).