PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.7680

eISSN 2348-1900

REVIEW ARTICLE

Revolutionizing weed management with nanotechnology: A review

Santhosh R[1], Vignesh M[1], Vikraman S U[2] & Selvakumar S[1]*

[1]Department of Agronomy, Agricultural College and Research Institute, Madurai 625 104, India
[2]Department of Soils and Environment, Agricultural College and Research Institute, Madurai 625 104, India

*Correspondence email - selvakumar.phdagr2021@tnau.ac.in

Received: 11 February 2025; Accepted: 20 March 2025; Available online: Version 1.0: 11 June 2025

Cite this article: Santhosh R, Vignesh M, Vikraman SU, Selvakumar S. Revolutionizing weed management with nanotechnology: A review. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.7680

Abstract

Nanotechnology offers innovative solutions across various fields, including agriculture. By manipulating matter at the nanoscale (1-100 nm), nanotechnology facilitates the development of more efficient, durable and environmentally sustainable agricultural products. Key applications include nano-fertilizers, nano-pesticides and nanoherbicides, which enhance crop yields while mitigating environmental impact. For instance, nanoherbicides provide improved efficacy and targeted weed control, addressing challenges associated with conventional herbicides, such as resistance and soil contamination. Furthermore, nanotechnology enables the development of controlled -release herbicide systems, reducing toxicity and enhancing crop safety. Additionally, nanoparticles play a crucial role in soil health, water purification and pest management. Nanoparticle production techniques, such as top-down and bottom-up approaches, enable precise material engineering for agricultural use. However, the potential adverse effects of nanomaterials, such as toxicity and cellular damage in plants, necessitate careful consideration. The integration of nanotechnology in agriculture promises increased productivity, environmental sustainability and enhanced food safety. Continued research and development are essential to address the challenges and optimize the benefits of nanotechnology in agriculture.

Keywords: bottom-up; nanoherbicides; top-down; weed seed bank

Introduction

The foundation of nanotechnology was laid by Richard Feynman in his 1959 lecture, ‘'There's Plenty of Room at the Bottom.' The term was later introduced by Norio Taniguchi in 1974. Subsequently, researchers have continued to investigate and develop various technologies and applications in the field of nanoscience. Nanotechnology, which focuses on manipulating matter on the nanoscale (1-100 nm). It is versatile because it allows for precise manipulation of materials at the atomic and molecular levels, enabling advancements in medicine, electronics, energy and materials science. This precision leads to innovations such as targeted drug delivery, highly efficient sensors, stronger yet lighter materials and improved energy storage solutions. These advancements are anticipated to have widespread applications across various sectors, including household items, communication, medicine, agriculture and the food industry (1). Nanotechnology-based products and applications in agriculture include nano-fertilizers, nanoherbicides and nano-pesticides for improved crop protection and growth; nanoscale carriers and nano-sensors for efficient nutrient delivery and deficiency detection; water purification through removal of persistent contaminants and photocatalysis; and advanced preservation techniques using nano-barcodes and quantum dots. Weeds pose a significant threat to agriculture, particularly in vulnerable agroecosystems. Vulnerable agroecosystems refer to agricultural systems that are highly susceptible to environmental and socio-economic challenges. These include climate-prone regions affected by extreme weather conditions (droughts, floods and temperature fluctuations) and resource-limited areas with poor soil quality, water scarcity, or lack of access to essential agricultural inputs. Such ecosystems are at greater risk of reduced productivity, biodiversity loss and food insecurity where crop yields can be compromised. Most herbicides are designed to eliminate or manage the aboveground parts of the weeds. However, rhizomes and tubers, which serve as sources for new weed growth throughout the growing season, remain unaffected by certain herbicides that do not penetrate the soil, as they are located below the surface (2). Enhancing herbicide effectiveness using nanotechnology may result in increased crop yields. Nanoherbicides utilize nanoscale carriers or nanomaterial-based formulations to enhance the targeted and efficient delivery of active ingredients. Concerns regarding food and environmental contamination have intensified because of the excessive and improper use of conventional chemical herbicides. Compared with traditional herbicides, nanomaterial-based formulations offer improved solubility, enhanced efficacy and reduced toxicity. These herbicides are coated with nanomaterials to enhance their bioavailability and improve weed control (3).

Incorporating new technologies in agriculture, including advanced monitoring systems, smart chemicals, gene delivery for crops, nanoherbicides and nanoformulations, is set to revolutionize the industry (4). These technological improvements enhance efficiency and decrease indirect agricultural waste by reducing environmental pollution. Therefore, it seems crucial to incorporate nanotechnology into farming practices and continue research and practical implementation in this field (5).

What is nanotechnology?

The term "nano" comes from the Greek word meaning "dwarf" or "small". Nanotechnology primarily involves the Processing of materials which refers to the precise manipulation, modification and engineering of materials at the nanoscale to enhance their physical, chemical and biological properties for specific applications. According to the US Environmental Protection Agency (2007), nanotechnology is the science of understanding and controlling matter at scales of approximately 1-100 nm, where distinct physical properties enable new and innovative applications (6). From an agricultural viewpoint, nanoparticles are generally defined as particles ranging from 1 to 100 nm in size. However, some broader definitions in agricultural applications may extend this range up to 1000 nm, depending on functional properties and behavior exhibiting both colloidal and particulate characteristics. Nanotechnology is the science and technology focused on materials typically smaller than 100 nm, with one nanometer equaling 10^{-9} m. It combines with various fields such as solid-state physics, chemistry, chemical engineering, biochemistry, biophysics and materials science Nanotechnology represents an innovative scientific approach that utilizes materials and devices to harrness the unique physical and chemical properties of substances at the molecular level. This allows for the exploration of biological and material systems at the nanoscale, with applications ranging from medicine to agriculture (7).

Nanoparticles

A nanoparticle is defined as a particle, either of natural or manufactured origin, with at least one dimension within the 1 to 100 nm range (Fig. 1). A nanometer is one billionth of a meter. Nanoparticles are utilized in various applications such as nanoemulsions, carbon nanotubes (CNTs), quantum dots, nanorods and micro and nanoencapsulation (8). Nanoparticles, generally ranging in size from 1 nm to 100 nm, possess unique physical properties that differ from those of bulk materials (9). Examples include nanoemulsions, CNTs, quantum dots, nanorods and materials encapsulated at the micro or nanoscale. Significant characteristics of nanoparticles include their morphology, hydrophobicity and solubility. Additionally, their surface properties such as area, roughness, potential contamination, adsorption during synthesis and ability to release toxic species also play a crucial role in their behavior. Additional critical factors include their ability to generate reactive oxygen species (ROS) with O_2 and H_2O, their structure, composition, competitive receptor binding sites and tendencies for dispersion and aggregation, which have been extensively studied (10).

Techniques for producing nanoparticles

The Royal Society and the Royal Academy of Engineering state that nanomaterials can be prepared through two primary approaches: a top-down method, which involves reducing the size of bulk materials and a bottom-up technique, which builds materials at the atomic level (12).

Top-down approach

This method involves the bulk materials being broken down into smaller nanoscale structures, resulting in a broad size distribution to create intricate patterns using mechanical and physical techniques such as grinding, milling and crushing to produce nanoparticles. In the aerospace and automotive sectors, it improves lightweight, durable materials for aircraft parts, coatings and engine components. The electronics and semiconductor industries employ nano-grained metallic and ceramic substances for microelectronics, sensors and advanced coatings. In the biomedical field, it aids in creating nanoparticles for drug delivery, medical implants and biosensors. It is commonly used to fabricate nanocomposites and nano-grained bulk materials, such as metallic and ceramic nanomaterials, with a broad size distribution ranging from (10 to 1000 nm) as shown in Fig. 2.

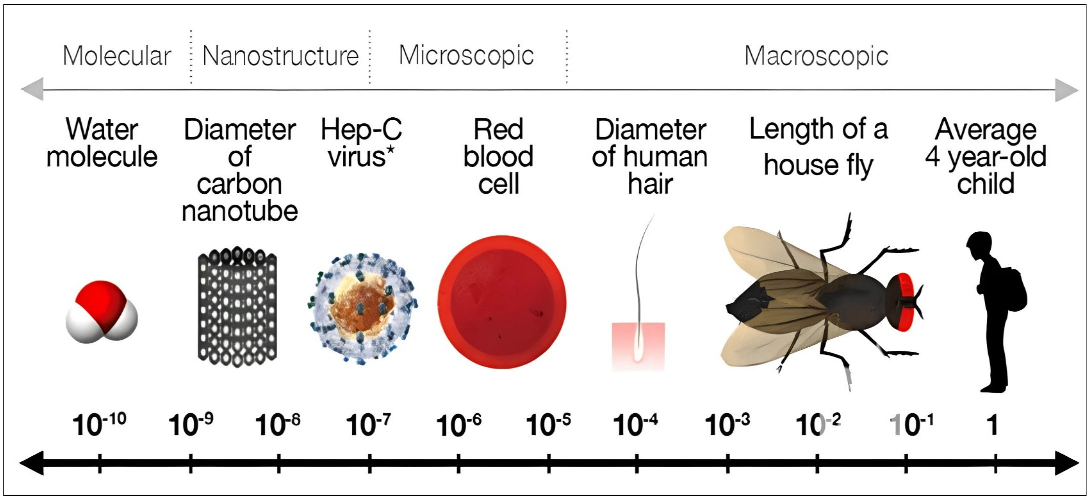

Fig. 1. Scale of nanoparticles (11).

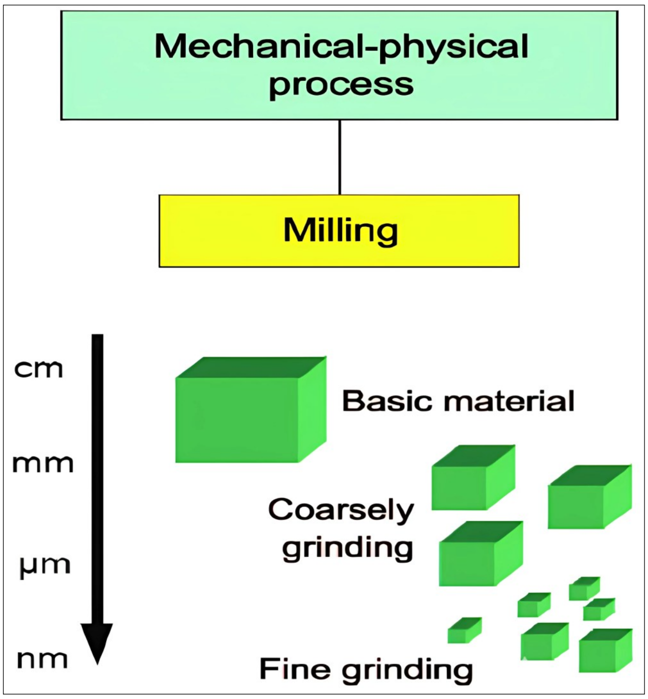

Fig. 2. Mechanical process for creating nanoparticles (12).

Bottom-up system

In the Bottom-up approach, multiple molecules undergo self-assembly through parallel steps based on their molecular recognition properties, facilitating the formation of complex structures from atoms or molecules. This method allows for precise control over the size, shape and size distribution of nanomaterials (Fig. 3). Examples of self-assembly processes include chemical vapour deposition (CVD), widely used in semiconductor fabrication and sol-gel synthesis, commonly employed in producing metal oxides, coatings and catalysts. These techniques enable the controlled growth of nanomaterials with specific properties, making them essential in electronics, optics and biomedical applications.

Advancement of nanotechnology in agriculture

Nanotechnology has emerged as a promising tool in agriculture, offering solutions to some of the industry's biggest challenges, such as food security, crop productivity, environmental sustainability and the effects of climate change. Advancements in nanotechnology in agriculture span across several areas, including crop protection, nutrient delivery, soil management, pest control and even food safety (Table 1).

Table 1. Some key advancements and applications of nanotechnology in agriculture

Application	Nanomaterial	Function/Benefits	Reference
Nanofertilizer matrix and coating designs	•Chitosan, Alginate,Gelatin •Graphene •Carbon Nanotubes •Hydroxyapatite	•Slow, sustained, or targeted nutrient release is synchronized with crop demand. •Markedly reduces nutrient losses.	(14)
Encapsulation of garlic essential oil in fertilizers	•Chitosan nanoparticles	•The bioactivity of garlic essential oil was preserved. •Induced 22-55 % increase in wheat grain yield under stress conditions	(15)
Plant health and disease diagnosis	•Quantum dot nanoprobes •Gold nanoparticle-based assays	•Highly sensitive and rapid nano biosensors for on-site monitoring of plant health enable quick and accurate assessment of plant conditions in real time. •Quick detection of plant pathogens in field samples, before symptom onset	(16)
Insect and pest detection	•Carbon nanotube gas sensors • Aptamer-based electrochemical sensors	•Sensitive on-site detection of insects and pests allows for the quick and accurate identification of pests in their natural environment, enabling timely management and control. •Rapid detection of insect pheromones or wing vibrations from low pest populations. Enabling prompt control interventions.	(17)
Water purification for irrigation	•Graphene oxide nanofiltration membranes	•High-performance nanomembranes demonstrated 98 % rejection of salt ions and micropollutants in field drainage water. •Produces excellent quality water for crop irrigation.	(18)
Real-time irrigation scheduling	•Wireless nanosensor networks. •Tensiometer nanosensors. •Infrared nanosensor films	•Precise irrigation scheduling for optimal water use efficiency. •Tensiometer nanosensors measure water potential in situ, triggering irrigation when needed. •Infrared films detect water stress onset early.	(19)
Soil moisture retention enhancement	•Hydrophilic nanomaterials. •Nanoclay minerals. •Cellulose nanofiber amendments	•Nanoclays improve soil moisture retention, reducing irrigation needs. •Increased available soil water content in sandy soils. •Cellulose nanofibers nearly doubled the plant-available water in light soils.	(20)

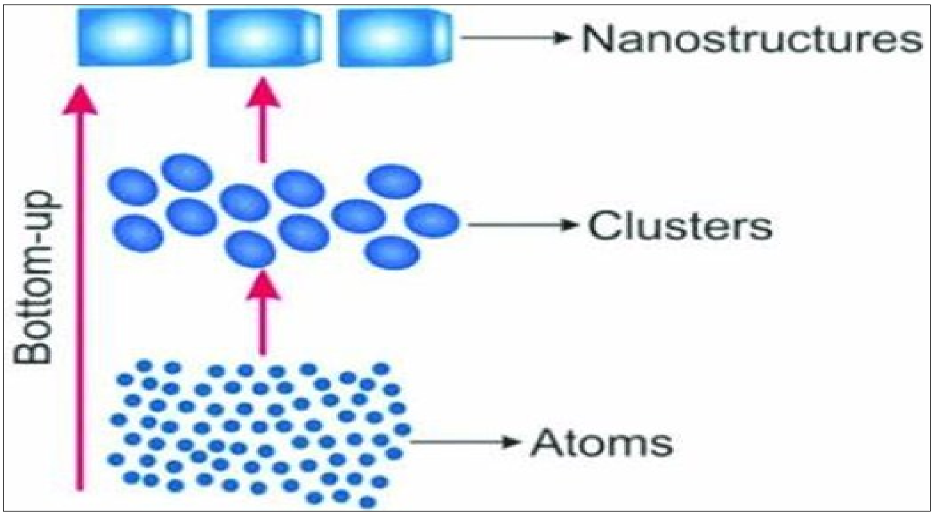

Fig. 3. The structures of nanoparticles created through chemical methods (13).

Nanoherbicides

In agriculture, where labor is intensive, costs are high and environmental hazards are present, nanoherbicides offer significant potential for eliminating weeds from fields with minimal labor and reduced environmental risk. Conventionally, herbicides are applied to standing crops to control weeds; however, this approach can adversely affect the crops and significantly reduce their yields (21). Nanoherbicides represent a viable tool for controlling weeds in sustainable agricultural practices. Certain compounds specific to these nanocarriers exhibit distinct morphological and physiological characteristics at sizes greater than 100 nm (22). These nanoherbicides have demonstrated increased efficacy due to a higher rate of diffusion, enhanced adhesion and extended contact times with the leaves. They effectively regulate the transport of ions and other biomolecules within plant cells (23). Nano MTZ (nano metribuzin) has been recognized as a highly potent weed control agent in agriculture (14). It is more effective than traditional herbicides, functioning at a lower rate (48 g ai/ha) to reduce pigment levels and inhibit Photosystem II activity. Additionally, it offers greater mobility, reduced retention in soils and no inhibitory effects on enzymatic processes. Various types of nanoherbicides have been proposed, utilizing both inorganic and organic nanocarriers.

Nanoencapsulation

Nanoencapsulation involves embedding active herbicide ingredients within nanometer-scale carriers such as liposomes, polymeric nanoparticles, or mesoporous silica nanoparticles. This approach enhances herbicide performance primarily by enabling the controlled release of the active ingredient. In a typical nano-encapsulated system, the herbicide is enclosed within a protective shell that gradually degrades under specific environmental conditions such as pH, temperature and humidity (24). This controlled-release mechanism allows the active ingredient to be delivered over an extended period, decreasing the need for multiple applications.

Nanoencapsulated herbicide

Herbicides can be applied through nanoencapsulation, where an active chemical is encapsulated within materials ranging from nano-to microscale, enabling controlled release to maintain weed-free conditions throughout the season. Encapsulated or coated substances are commonly referred to as the internal phase, filler, or core material (25). Nanoencapsulation of herbicides enables slow release, ensuring that active chemicals are available at the proper concentration for the appropriate duration to effectively target weeds without harming crop plants. Herbicides are coated with a semi-permeable membrane made from organic or inorganic polymers, which regulate their release and enhance efficiency. Examples of commonly used polymers include polyethylene glycol (PEG), widely used for controlled-release formulations and poly (lactic-co-glycolic acid) (PLGA), a biodegradable polymer commonly applied in agricultural and pharmaceutical industries. Additionally, chitosan, a natural biopolymer, is frequently used for its biodegradability and eco-friendly properties, while silicone-based polymers serve as inorganic alternatives for sustained herbicide release (26). These polymers help improve herbicide stability, reduce environmental impact and ensure targeted delivery, allowing them to dissolve in water and release active ingredients through mechanisms such as ion exchange, diffusion, osmotic pressure, or matrix degradation (Fig. 4).

Targeted delivery systems in nanoherbicides

A highly promising application of nanotechnology in agriculture is the creation of targeted delivery systems for herbicides. This system aims to deliver the active ingredient directly to the target weed, reducing the impact on non-target plants and the environment. Compared to conventional herbicide spraying, which often leads to significant drift, runoff and wastage, this controlled-release approach enhances efficiency by minimizing herbicide loss and ensuring sustained targeted delivery. As a result, lower doses can achieve the desired effect, reducing chemical usage, environmental contamination and costs while improving weed control effectiveness over time. This precision is achieved by functionalizing nanoparticles with ligands or antibodies that specifically bind to receptors on the surface of the target organism. For example, folic acid is a commonly used ligand that targets folate receptors, which are overexpressed in certain cancer cells. Similarly, monoclonal antibodies such as trastuzumab (Herceptin) can be used to bind to HER2 receptors on cancer cells, enabling highly specific drug delivery. These targeted approaches enhance treatment efficacy while

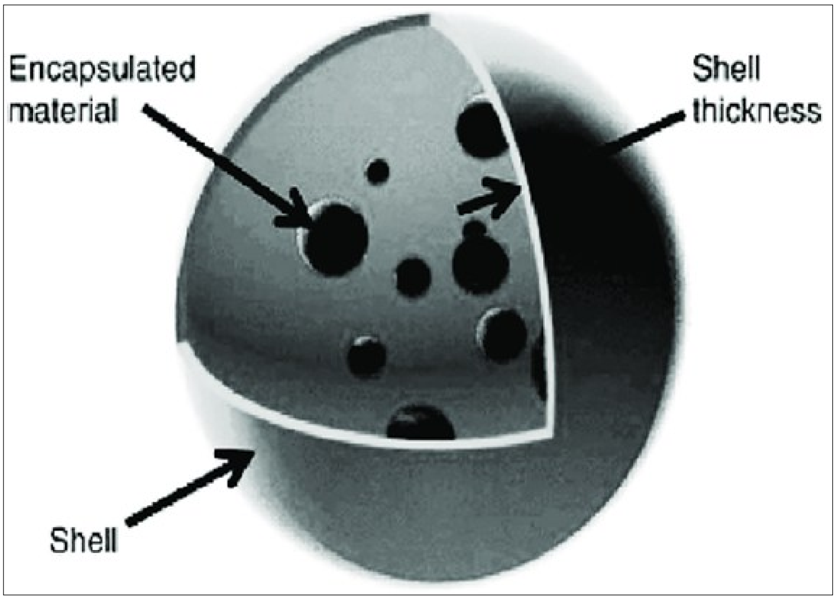

Fig. 4. Nanoencapsulated particles (26).

minimizing side effects on healthy cells. (27). This approach involves encapsulating the herbicide molecules within nanoparticles engineered to target specific receptors on weed roots. Once absorbed by the plant, the herbicide is transported to critical areas, where it disrupts glycolysis within the root system (28). Applying herbicides in rainfed areas with over 750 mm of annual rainfall can result in vaporization losses if soil moisture is low. Accurate rainfall prediction remains a challenge, complicating herbicide application timing (Fig. 5). Controlled release of encapsulated herbicides provides an effective solution for managing weeds, revolutionizing herbicide use. The nanotechnology revolution has introduced eco-friendly, cost-efficient nanoherbicides and offers effective weed control with minimal environmental impact (29).

Mechanisms of action of the nanoparticles used in weed management

Nanoherbicides represent a promising advancement in sustainable weed management, significantly impacting plant physiology, metabolism and biochemistry through multiple mechanisms. These nanoscale formulations alter gene expression, lipid peroxidation, chlorophyll and protein content and antioxidant activity while disrupting cell membranes, causing electrolyte leakage and oxidative stress. Plants attempt to mitigate these effects by compartmentalizing nanostructures into vacuoles. Nanoherbicides particularly affect mitochondria and chloroplasts by interfering with the electron transport chain (ETC), ROS production and photosynthesis, with ROS-related effects stemming from prooxidant functional groups, redox cycling and particle-cell interactions (Fig. 6). While their impact on mitochondrial function, including the tricarboxylic acid (TCA) cycle, remains under-researched, studies indicate that in chloroplasts, nanoherbicides can reduce PSII quantum yield, deactivate PSI and impair CO_2 assimilation. Research suggests that nanoencapsulation, such as polycaprolactone (PCL) nanocapsules, reduce herbicide toxicity, though nuclear penetration of nanoherbicides may still damage genetic material and alter transcriptomic behavior by upregulating antioxidant-related genes. Additionally, nanoherbicides influence protein and lipid production by targeting the endoplasmic reticulum (ER), potentially reducing protein synthesis while forming a protein corona that alters their biological interactions. Their cellular uptake occurs through passive diffusion or active endocytosis, differing from conventional herbicides in localization, as nanoherbicides may

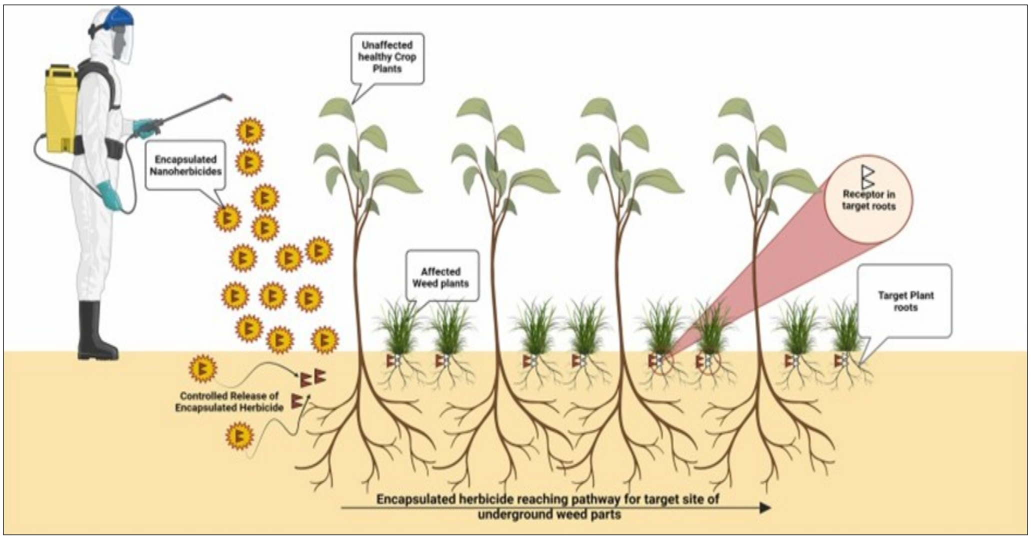

Fig. 5. A visual representation of the administration of nanoencapsulated herbicides in the crop-weed environment (30).

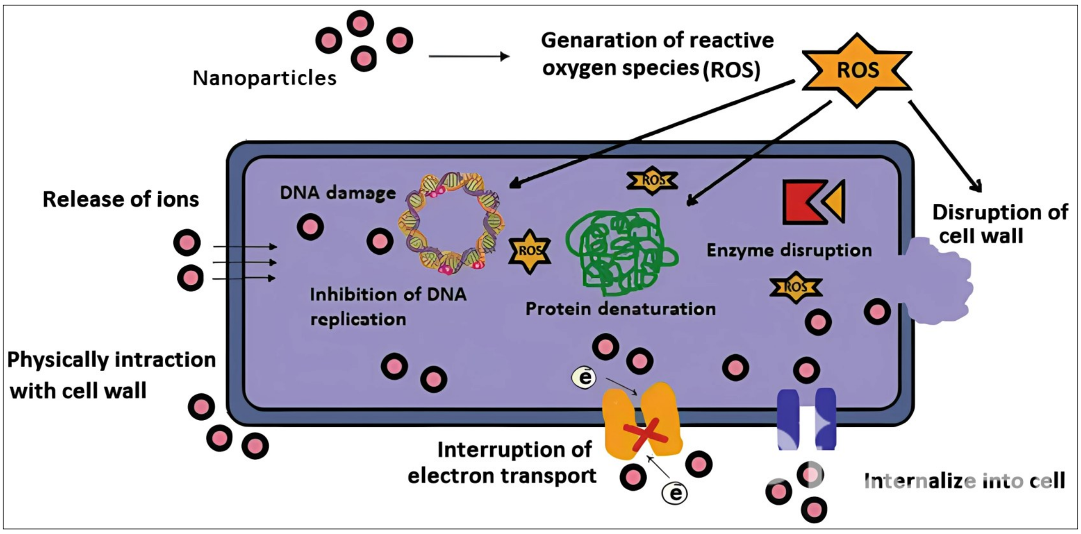

Fig. 6. Mechanisms of action of the nanoparticles.

accumulate in the Golgi apparatus near the nucleus, affecting intracellular trafficking. A critical research gap exists regarding their interactions with non-target plants and rhizosphere microbial communities, as studies on nanoatrazine indicate that prolonged exposure may disrupt bacterial populations and plant-soil dynamics. Mechanistically, nanoherbicides enhance herbicide delivery by improving solubility, stability and bioavailability, leading to controlled release, prolonged action and reduced environmental impact. For example, atrazine encapsulated in silica nanoparticles has been shown to enhance retention in weed tissues while reducing leaching. Furthermore, some nanoparticles physically disrupt weed germination and root development by forming coatings that block water absorption and gas exchange. One example of a weed species affected by silica and carbon-based nanoparticles is *Amaranthus retroflexus* (redroot pigweed). Studies have shown that these nanoparticles can alter soil properties, such as water retention and nutrient availability, thereby inhibiting the germination and early growth of *Amaranthus retroflexus* seedlings. Additionally, metal and metal oxide nanoparticles (e.g., CuO, ZnO, TiO_2) generate ROS in plant tissues, causing oxidative stress, membrane damage and photosynthetic disruption. Research on Amaranthus palmeri has shown that copper nanoparticles (CuNPs) decrease chlorophyll content and reduce weed viability. Nanoherbicides also interfere with nutrient uptake by chelating essential micronutrients such as iron (Fe) and zinc (Zn), reducing their bioavailability to weeds. Studies have found that ZnO and TiO_2 nanoparticles restrict nitrogen and phosphorus uptake, significantly lowering weed biomass. Nanoherbicides pose potential risks to beneficial soil microbes by disrupting microbial communities, altering enzyme activities and affecting nutrient cycling. Some nanoparticles may exhibit toxicity to essential bacteria and fungi, reducing their populations and impairing soil health. Additionally, long-term accumulation could lead to imbalances in microbial diversity, potentially affecting plant-soil interactions and ecosystem stability. However, comprehensive research is necessary to fully understand their long-term impacts on plant physiology, soil ecosystems and non-target species. Ensuring their safe and effective use requires further studies on their molecular interactions, ecological consequences and risks associated with prolonged exposure in agricultural environments.

Nano biosensors for herbicide residue detection

A nano biosensor for detecting herbicide residues is a cutting-edge technology designed to identify trace amounts of herbicides in environmental samples, such as soil, water, or food products (31). These sensors typically utilize nanomaterials, such as nanoparticles, nanowires, or CNTs, which enhance the sensitivity and specificity of detection due to their large surface area and unique electronic properties. The biosensor works by immobilizing a bio-recognition element (such as an enzyme, antibody, or receptor) onto the surface of the nanomaterial. This recognition element interacts specifically with the target herbicide molecules, triggering a measurable signal, often in the form of optical, electrochemical, or mass-based responses (32).

In the case of herbicide detection, the biosensor can be tailored to recognize specific herbicide molecules, such as glyphosate, diclofop, or atrazine, through molecular interactions. The presence of the herbicide changes the properties of the nanomaterial or the bio-recognition element, leading to a detectable change in the signal (33). The sensitivity of these sensors allows for the detection of herbicide concentrations at very low levels, well below the regulatory limits. Additionally, their portability and rapid response times make nano biosensors ideal for on-site environmental monitoring and food safety applications. These sensors are considered an important tool for ensuring the safety of ecosystems and human health, as they enable real-time, accurate and cost-effective detection of herbicide contamination (34).

To increase yield, chemical herbicides have become increasingly popular since the Green Revolution. While farmers have seen success in terms of output, food materials will inevitably become contaminated with chemical herbicides, posing threats to human health and food safety (35). About 40 % of the global herbicide market consists of the two most commonly used herbicides, atrazine and glyphosate (36). The enzyme acetylcholinesterase (AChE), which catalyzes the breakdown of the neurotransmitter acetylcholine, plays a significant role in our body. Herbicide toxins in food have a devastating effect on human health because they primarily inhibit this enzyme's function. To prevent this, food items should be examined and the level of herbicide residues should be determined before consumption. Although numerous chromatographic techniques (such as GC and HPLC) and linked chromatographic-spectrometric processes (like GC–MS and HPLC-MS) are commercially available, these technologies can be expensive and are often incapable of performing real-time analysis. AChE activity is typically measured using the colorimetric Ellman assay both before and after exposure to herbicides to detect them (37).

Biosensors based on AuNPs (3 nm) nanoparticles have been used to detect a variety of herbicide molecules, including paraquat, oxyfluorfen, diquat and bromoxynil, at concentrations of 24 µg/mL. A chemiluminescence (CL) "fingerprint" associated with each herbicide was created by combining Lum-AgNPs with an H_2O_2-based CL detection method. Recently, a chitosan-TiO_2 graphene nanocomposite-based biosensor for the detection of atrazine in groundnuts was developed. This biosensor is highly stable and reproducible, with the nanocomposite's porosity effectively immobilizing enzymes, thus enhancing the biosensor's stability (38).

Weed seed bank exhaustion

The utilization of nanoparticles for the depletion of weed seed banks represents an emerging approach in environmental and agricultural research. Nanoparticles inhibit weed seed germination through multiple mechanisms, including forming a physical barrier that alters soil structure and reduces water and oxygen availability, generating ROS that induce oxidative stress and damage seed cells, interfering with plant hormone signaling (e.g., gibberellins and abscisic acid) to disrupt germination and sequestering essential nutrients, limiting their availability to seeds. These interactions collectively suppress weed emergence from the soil seed bank, reducing competition in agricultural fields (Table 2). Consequently, this strategy may reduce dependence on conventional herbicides and contribute to addressing the escalating issue of herbicide-resistant weeds (39).

Detoxification of herbicide

Detoxification is a reliable strategy to lower the toxic levels of herbicides and enhance the plant's resistance to the chemical (45). The detoxification of herbicide residues using nanoparticles is one of the most significant applications of nanotechnology in agriculture. Studies have demonstrated that the overuse of herbicides and the accumulation of their residues in soil can harm crops. Prolonged reliance on a single herbicide promotes the development of herbicide-resistant weed species and alters weed flora composition. The application of herbicides has significantly harmed the environment, with their persistence and contamination potential posing major challenges to human health and environmental safety (46). Carbon-based nano-adsorbents, such as CNTs, represent an emerging class of nanomaterials with significant potential for removing various herbicide residues from soil. Similarly, graphene, another carbon nanomaterial, holds immense promise in water purification and other applications due to its distinctive physical and chemical properties. Nanocrystalline metal oxides, including ferric, manganese, aluminium, titanium, magnesium and cerium oxides, serve as highly efficient adsorbents for a wide range of herbicides. Beyond adsorption, these nanomaterials can neutralize chemical hazards by transforming them into safer by-products. Combining bioaugmentation and bio-stimulation with the addition of organic matter offers a promising approach for enhancing the biodegradation of herbicides in soil (47, 48).

Nanoencapsulation of herbicides enables controlled slow release

Nanoencapsulation of herbicides enables controlled, slow release, improving the efficiency and environmental safety of weed management practices. This process involves encapsulating herbicides within a semi-permeable membrane made from organic or inorganic polymers, which serves as a protective barrier regulating the release of active ingredients through mechanisms such as diffusion, ion exchange and external stimuli response. Using nanoparticles for herbicide encapsulation ensures a gradual, sustained release, maintaining optimal concentration of the active ingredient for effective weed control and reducing the frequency of applications. This controlled release mechanism enhances the herbicide's bioavailability, minimizes volatilization and leaching losses and prevents rapid degradation due to environmental factors such as UV radiation and microbial activity. Moreover, nanoencapsulation significantly mitigates the potentially toxic effects of herbicides on soil biodiversity by preventing excessive accumulation in non-target areas, thereby preserving beneficial soil microorganisms and promoting long-term soil health. The reduced off-target movement of herbicides lowers the risk of groundwater contamination and non-selective toxicity to crops and surrounding vegetation. Additionally, nanoencapsulation allows for the development of targeted delivery systems, where surface modifications enable herbicide nanoparticles to interact selectively with weed species, enhancing herbicidal efficacy

Table 2. Key approaches to using nanoparticles for weed seed bank exhaustion

Nanoparticles	Effects	Reference
Ag/Na nanoparticles	•Dehydration of pollen grains •Induces sterility in weed flowers •Preventing seed production.	(40)
Use of Carbon Nanotubes (CNTs)	•Render seeds are non-viable instead of targeting seedlings. •Acts as conduits for water and chemical	(41)
Nanoencapsulation of triazine	•Significantly increases mortality rates in seedlings (e.g., *B. pilosa*). •Reduces atrazine mobility in soil.	(42)
Nano formulation		(43)
pre-emergence herbicide pendimethalin in combination with silver nanoparticles and hydrogen	•Reduction in the enlargement of future soil weed seed bank.	(44)

while minimizing adverse effects on crops and beneficial organisms. Encapsulated formulations also improve herbicide stability under varying environmental conditions, extending shelf life and ensuring consistent field performance. By offering precise and controlled herbicide delivery, nanoencapsulation technology represents a significant advancement in sustainable agriculture, contributing to improved weed management practices while reducing the environmental footprint of chemical herbicides. However, further research is needed to optimize encapsulation materials, assess long-term environmental impacts and ensure large-scale applicability without unintended ecological consequences.

Eco-friendly of nanoherbicides

Nanoherbicides inhibit leaching, volatilization and premature degradation of active ingredients through various mechanisms. The encapsulation of herbicides at the nanoscale results in more targeted and environmentally sustainable agricultural formulations. The use of nanoherbicides in reduced quantities offers several advantages such as mitigating the persistent effects of herbicide residues in agricultural fields and diminishing their environmental toxicity. Furthermore, it facilitates weed elimination without adversely affecting crop plants, ultimately leading to enhanced crop yield (49). Nanoherbicide delivery systems incorporate five stimuli-responsive features to achieve a controlled release of the encapsulated PQ herbicide. These five stimuli - acidic pH, basic pH, GSH, phosphate and EDTA, are closely associated with physiological and environmental factors in plants. Upon entering plants or soil, eco-friendly nanocarriers degrade, thereby preventing bioaccumulation (50). Given the challenges in translating research findings and identifying alternative herbicides for weed management, PCL nanoparticles have been developed for the sustainable use of bioactive compounds. These nanoparticles are utilized to create nanoherbicides containing triazine-class chemicals (ametrine, atrazine and simazine), polycaprolactone and metribuzin (51). PCL is particularly valuable for encapsulating herbicides, especially atrazine-based ones, due to its readily modifiable chemical composition, biodegradability, biocompatibility, controlled distribution, high colloidal stability of molar masses and controllable architectures. These properties render herbicides environmentally sustainable. Currently, nanoprecipitation and emulsion-solvent diffusion techniques are employed to produce PCL nanoherbicides, such as nano-PCL-atrazine and nano-PCL-metribuzin (52).

Advantages of nanoencapsulation in herbicide delivery

The application of nano-encapsulated herbicides offers several benefits over conventional formulations:

Prolonged herbicidal activity

The slow and controlled release ensures a sustained effect, reducing the need for frequent herbicide applications and lowering input costs for farmers.

Reduced environmental impact

By minimizing herbicide runoff, volatilization and leaching, nanoencapsulation mitigates contamination of groundwater and nearby ecosystems, promoting environmental safety.

Enhanced targeted delivery

Nanoencapsulation allows for site-specific herbicide delivery, reducing non-target effects on beneficial soil microbes, crops and surrounding flora.

Minimization of phytotoxicity and soil toxicity

Traditional herbicides, when applied in high doses, can accumulate in the soil and negatively impact microbial diversity. Controlled release through nanoencapsulation ensures that only the necessary concentration reaches the weeds, protecting soil biodiversity.

Improved herbicide stability

Encapsulation enhances the stability of herbicides against environmental degradation, such as UV radiation, hydrolysis and microbial breakdown, extending their shelf life and effectiveness.

Compatibility with sustainable agriculture

Nanoencapsulation aligns with precision agriculture by reducing herbicide waste and improving resource efficiency, thereby supporting sustainable weed management practices.

Negative effects of nano materials in plants

✓ Nanomaterials like titanium dioxide (TiO_2 NPs), zinc oxide (ZnO NPs) and silver (AgNPs) can generate ROS in plant cells, damaging proteins, lipids, DNA and cell membranes, leading to cellular stress or death (53).

✓ Nanoparticle accumulation on leaf surfaces and within tissues may reduce light absorption and chlorophyll production, impairing photosynthesis.

✓ Some nanomaterials adhere to roots or alter membrane permeability, disrupting essential nutrient absorption (54).

✓ High concentrations of metal-based nanoparticles can reduce seed germination and delay seedling growth.

✓ Nanoparticles like CNTs, silver and zinc oxide may also cause DNA damage and genetic instability, affecting future plant generations.

Conclusion

The future potential of nanoherbicides lies in large-scale optimization, long-term environmental impact assessment and regulatory development. Nanotechnology holds transformative potential, particularly in enhancing weed management and improving overall sustainability. The integration of nanoherbicides, nanoencapsulation and targeted delivery systems addresses the limitations of traditional chemical herbicides by enabling the precise and controlled application of active ingredients, reducing environmental contamination and minimizing harm to non-target organisms. Additionally, nano-biosensors offer innovative solutions for detecting herbicide residues, ensuring food safety and monitoring the environment. Nanoparticles can also be utilized for the detoxification of persistent herbicide residues, contributing to healthier ecosystems. However, widespread adoption requires optimizing nanoherbicides for large-scale use through improved formulation stability and integration with precision agriculture technologies such as drone-based spraying and smart sensors. Their long-term environmental effects must be studied, including their persistence in soil, interactions with beneficial microbes and potential toxicity to non-target organisms. Regulatory frameworks must establish safety guidelines, risk assessments and standardized approval processes while ensuring public awareness and acceptance. Continued research and development are essential for overcoming challenges such as cost, scalability and regulatory approvals, ultimately paving the way for a more sustainable and efficient agricultural future.

Acknowledgements

We extend our sincere thanks to the Tamil Nadu Agricultural University in Coimbatore and the Agricultural College and Research Institute located in Madurai for providing essential technical assistance and expert advice.

Authors' contributions

SR collected the literature and drafted the manuscript, while SS provided overall guidance for corrections and improvements. VM and VSU assisted with literature collection and formatting. All authors contributed equally to revising the manuscript and approved the final draft.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process : During the preparation of this work, I used ChatGPT to improve my language. After using this tool, I reviewed and edited the content as needed and take full responsibility for the publication.

References

1. Prasad R, Kumar V, Prasad KS. Nanotechnology in sustainable agriculture: present concerns and future aspects. Afr J Biotechnol. 2014;13(6):705–13. https://doi.org/10.5897/AJBX2013.13554
2. La Iacona M, Scavo A, Lombardo S, Mauromicale G. The Exploitation of Nanotechnology in Herbicides and Bioherbicides: A Novel Approach for Sustainable Weed Management. Agronomy. 2025;15 (1):228. https://doi.org/10.3390/agronomy15010228
3. Amna, Alharby HF, Hakeem KR, Qureshi MI. Weed control through herbicide-loaded nanoparticles. Nanomaterials and plant potential. 2019:507–27. https://doi.org/10.1007/978-3-030-05569-1_20
4. Bhattacherje R, Ghosh S, Banerjee D. 4 Insects and nanoparticles. In: Immune System of Animals Volume 2. Berlin, Boston: De Gruyter; 2022. p. 61–88. https://doi.org/10.1515/9783110655872-004
5. Bindu VK, Fathima P, Yogananda S, Roopashree D. A review on nanotechnology in weed management. Mysore J. Agric Sci. 2023;57 (4):1.
6. Bueno CC, Amarante AM, Oliveira GS, Deda DK, Teschke O, de Faria Franca E, et al. Nanobiosensor for diclofop detection based on chemically modified AFM probes. IEEE Sensors J. 2014;14(5):1467–75. https://doi.org/10.1109/JSEN.2014.2301997
7. Chinnamuthu CR, Kokiladevi E. Weed management through nanoherbicides. Application of nanotechnology in agriculture. 2007;10:978–1.
8. Buffle J. The key role of environmental colloids/nanoparticles for the sustainability of life. Environ Chem. 2006;3(3):155–58. https://doi.org/10.1071/ENv3n3_ES
9. Christopher FC, Kumar PS, Christopher FJ, Joshiba GJ, Madhesh P. Recent advancements in rapid analysis of pesticides using nano biosensors: a present and future perspective. J Cleaner Prod. 2020;269:122356. https://doi.org/10.1016/j.jclepro.2020.122356
10. da Silva AC, Deda DK, Bueno CC, Moraes AS, Da Roz AL, Yamaji FM, et al. Nanobiosensors exploiting specific interactions between an enzyme and herbicides in atomic force spectroscopy. J Nanosci Nanotech. 2014;14(9):6678–84. https://doi.org/10.1166/jnn.2014.9360
11. Du H, Xie Y, Wang J. Nanomaterial-sensors for herbicides detection using electrochemical techniques and prospect applications. TrAC Trends Anal Chem. 2021;135:116178. https://doi.org/10.1016/j.trac.2020.116178
12. Emamverdian A, Ghorbani A, Li Y, Pehlivan N, Barker J, Ding Y, et al. Responsible mechanisms for the restriction of heavy metal toxicity in plants via the co-foliar spraying of nanoparticles. Agronomy. 2023;13(7):1748. https://doi.org/10.3390/agronomy13071748
13. Fahad F, Al-Hashimi RA, Hussain MJ. The Advancement in irrigation solution within the field of endodontics: A Review. J Baghdad Coll Dent. 2024;36(1):54–69. https://doi.org/10.26477/jbcd.v36i1.3591
14. Fakruddin M, Hossain Z, Afroz H. Prospects and applications of nanobiotechnology: a medical perspective. J Nanobiotechnol. 2012;10:1–8. https://doi.org/10.1186/1477-3155-10-31
15. Franca EF, Leite FL, Cunha RA, Oliveira Jr ON, Freitas LC. Designing an enzyme-based nanobiosensor using molecular modeling techniques. Phys Chem Chem Phys. 2011;13(19):8894–99. https://doi.org/10.1039/C1CP20393B
16. Ghaffar N, Farrukh MA, Naz S. Applications of nanobiosensors in agriculture. Nanoagronomy. 2020:179-96. https://doi.org/10.1007/978-3-030-41275-3_10
17. Grillo R, Pereira AE, Nishisaka CS, De Lima R, Oehlke K, Greiner R, et al. Chitosan/tripolyphosphate nanoparticles loaded with paraquat herbicide: an environmentally safer alternative for weed control. J Hazard Mater. 2014;278:163–71. https://doi.org/10.1016/j.jhazmat.2014.05.079
18. Haris M, Hussain T, Mohamed HI, Khan A, Ansari MS, Tauseef A, et al. Nanotechnology–A new frontier of nano-farming in agricultural and food production and its development. Sci Total Environ. 2023;857:159639. https://doi.org/10.1016/j.scitotenv.2022.159639
19. Jafir M, Irfan M, Zia-ur-Rehman M, Hafeez F, Ahmad JN, Sabir MA, et al. The global trend of nanomaterial usage to control the important agricultural arthropod pests: A comprehensive review. Plant Stress. 2023;10:100208. https://doi.org/10.1016/j.stress.2023.100208
20. Javaid M, Naeem-Ullah U, Khan WS, Saeed S, Qayyum MA, Khan MA. Role of nanotechnology in crop protection and production: A review. J Innov Sci. 2020;6(2):221–27.
21. Joshi H, Choudhary P, Mundra SL. Future prospects of nanotechnology in agriculture. Int J Chem Stud. 2019;7(2):957–63.
22. Maruyama CR, Guilger M, Pascoli M, Bileshy-José N, Abhilash PC, Fraceto LF, et al. Nanoparticles based on chitosan as carriers for the combined herbicides imazapic and imazapyr. Sci Rep. 2016 Jan 27;6 (1):19768. https://doi.org/10.1038/srep19768
23. Khodakovskaya M, Dervishi E, Mahmood M, Xu Y, Li Z, Watanabe F, et al. Carbon nanotubes are able to penetrate the plant seed coat and dramatically affect seed germination and plant growth. ACS Nano. 2009;3(10):3221–27. https://doi.org/10.1021/nn900887m
24. Kumari G, Kalita S, Hussain Z, Deka NC, Meena BR. Nanoencapsulation to control herbicide residues and resistance: A review. Asian J Microbiol Biotechnol Environ Sci. 2021;23:140–48.

25. Matter IA, Darwesh OM, Matter HA. Nanosensors for herbicides monitoring in soil. In: Nanomaterials for Soil Remediation. Elsevier; 2021. p. 221–37. https://doi.org/10.1016/B978-0-12-822891-3.00011-6

26. Muchhadiya RM, Kumawat PD, Sakarvadia HL, Muchhadiya PM. Weed management with the use of nano-encapsulated herbicide formulations: A review. J Pharm Innov. 2022;11:2068–75.

27. Murphy SD. The role of pollen allelopathy in weed ecology. Weed Technol. 2001;15(4):867–72. https://doi.org/10.1614/0890-037X(2001)015[0867:TROPAI]2.0.CO;2

28. Nakache E, Poulain N, Candau F, Orecchioni AM, Irache JM. Biopolymer and polymer nanoparticles and their biomedical applications. In: Handbook of nanostructured materials and nanotechnology. Academic Press; 2000. p. 577–635. https://doi.org/10.1016/B978-012513760-7/50063-0

29. Nasrollahzadeh M, Sajadi SM, Sajjadi M, Issaabadi Z. An introduction to nanotechnology. In: Interface science and technology Vol. 28. Elsevier; 2019. p. 1–27. https://doi.org/10.1016/B978-0-12-813586-0.00001-8

30. Pathak J, Singh DK, Singh PR, Kumari N, Jaiswal J, Gupta A, et al. Application of nanoparticles in agriculture: nano-based fertilizers, pesticides, herbicides and nanobiosensors. In: Molecular Impacts of Nanoparticles on Plants and Algae. Academic Press; 2024. p. 305–31. https://doi.org/10.1016/B978-0-323-95721-2.00012-9

31. Pramanik P, Krishnan P, Maity A, Mridha N, Mukherjee A, Rai V. Application of nanotechnology in agriculture. In: Environmental nanotechnology. Volume 4. 2020:317–48. https://doi.org/10.1007/978-3-030-26668-4_9

32. Preisler AC, Pereira AE, Campos EV, Dalazen G, Fraceto LF, Oliveira HC. Atrazine nanoencapsulation improves pre-emergence herbicidal activity against *Bidens pilosa* without enhancing long-term residual effect on Glycine max. Pest Manag Sci. 2020;76(1):141–49. https://doi.org/10.1002/ps.5482

33. Ribeiro LF, Reddy KR, Chetri JK. Nanobioremediation of insecticides and herbicides. In: Nano-Bioremediation: Fundamentals and Applications. Elsevier; 2022. p. 501–16. https://doi.org/10.1016/B978-0-12-823962-9.00002-7

34. Rani N, Duhan A, Pal A, Kumari P, Beniwal RK, Verma D, et al. Are nano-pesticides really meant for cleaner production? An overview on recent developments, benefits, environmental hazards and future prospectives. J Cleaner Prod. 2023;411:137232. https://doi.org/10.1016/j.jclepro.2023.137232

35. Saha B, Biswas S, Datta S, Mojumdar A, Pal S, Mohanty PS, et al. Sustainable Nano Solutions for Global Food Security and Biotic Stress Management. Plant Nano Biol. 2024:100090. https://doi.org/10.1016/j.plana.2024.100090

36. Salouti M, Khadivi Derakhshan F. Biosensors and nanobiosensors in environmental applications. In: Biogenic nanoparticles and their use in agro-ecosystems. 2020. p. 515–91. https://doi.org/10.1007/978-981-15-2985-6_26

37. Sarmah K, Borah R, Boruah S, Sarmah D. Nanopesticides: Revolutionizing pest management with nanotechnology. Biol Forum. 2023;15(7):210–18.

38. Sharma N, Singh S, Sondhia S. Recent advances in mitigation methods for herbicide residues in the soil. Indian J Weed Sci. 2020;52(4):300–08. https://doi.org/10.5958/0974-8164.2020.00060.X

39. Shimabukuro RH. Detoxication of herbicides. In: Weed physiology. Boca Raton (FL): CRC Press; 2018. p. 215–40. https://doi.org/10.1201/9781351077736-9

40. Singh RP. Recent trends, prospects and challenges of nanobiosensors in agriculture. In: Biosensors in agriculture: Recent trends and future perspectives. 2021. p. 3–13. https://doi.org/10.1007/978-3-030-66165-6_1

41. Somasundaran P, Fang X, Ponnurangam S, Li B. Nanoparticles: Characteristics, mechanisms and modulation of biotoxicity. Kona. 2010;28:38–49. https://doi.org/10.14356/kona.2010007

42. Songa EA, Waryo T, Jahed N, Baker PG, Kgarebe BV, Iwuoha EI. Electrochemical nanobiosensor for glyphosate herbicide and its metabolite. Electroanalysis. 2009;21(3-5):671–74. https://doi.org/10.1002/elan.200804452

43. Susha VS, Chinnamuthu CR, Pandian K. Remediation of herbicide atrazine through metal nanoparticles. Presented at: International Conference on Magnetic Materials and their Applications in the 21st Century; 2008 Oct 21; India. p. 21–23.

44. Takeshita V, Carvalho LB, Galhardi JA, Munhoz-Garcia GV, Pimpinato RF, Oliveira HC, et al. Development of a preemergent nanoherbicide: From efficiency evaluation to the assessment of environmental fate and risks to soil microorganisms. ACS Nanoscience Au. 2022;2(4):307–23. https://doi.org/10.1021/acsnanoscienceau.1c00055

45. Vishwakarma K, Upadhyay N, Kumar N, Tripathi DK, Chauhan DK, Sharma S, et al. Potential applications and avenues of nanotechnology in sustainable agriculture. In: Nanomaterials in plants, algae and microorganisms. Academic Press; 2018. p. 473–500. https://doi.org/10.1016/B978-0-12-811487-2.00021-9

46. Yadav AS, Srivastava DS. Application of nanotechnology in weed management: a review. Res Rev J Crop Sci Technol. 2015;4(2):21–23.

47. Zargar M, Bayat M, Romanova E, Izadi-Darbandi E. POST herbicide programs utilizing tribenuron for cleavers (*Galium aparine* L.) control in winter wheat cultivars. Arch Agron Soil Sci. 2020;66(9):1235–43. https://doi.org/10.1080/03650340.2019.1661995

48. Aslani F, Bagheri S, Muhd JN, Juraimi AS, Hashemi FS, Baghdadi A. Effects of engineered nanomaterials on plant growth: an overview. Sci World J. 2014;2014(1):641759. https://doi.org/10.1155/2014/641759

49. Verma SK, Das AK, Patel MK, Shah A, Kumar V, Gantait S. Engineered nanomaterials for plant growth and development: a perspective analysis. Sci Total Environ. 2018;630:1413-35. https://doi.org/10.1016/j.scitotenv.2018.02.313

50. Zhang X, Cao H, Wang H, Zhao J, Gao K, Qiao J, et al. The effects of graphene-family nanomaterials on plant growth: A review. Nanomaterials. 2022;12(6):936. https://doi.org/10.3390/nano12060936

51. Chichiriccò G, Poma A. Penetration and toxicity of nanomaterials in higher plants. Nanomaterials. 2015;5(2):851–73. https://doi.org/10.3390/nano5020851

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.