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Arun Kumar MR
Ph.D. Scholar, Department of Agronomy, College of Agriculture, V. C. Farm, Mandya, Karnataka, India

Fathima PS
Dean (Agri.), College of Agriculture, V. C. Farm, Mandya, Karnataka, India

Yogananda SB
Professor and Head, Department of Agronomy, College of Agriculture, V. C. Farm, Mandya, Karnataka, India

Dheeraj M
Ph.D. Scholar, Department of Agronomy, College of Agriculture, V. C. Farm, Mandya, Karnataka, India

Giridhar M
Ph.D. Scholar, Department of Agronomy, College of Agriculture, V. C. Farm, Mandya, Karnataka, India

Corresponding Author:
Arun Kumar MR
Ph.D. Scholar, Department of Agronomy, College of Agriculture, V. C. Farm, Mandya, Karnataka, India

Nanotechnology interventions for advanced weed management

Arun Kumar MR, Fathima PS, Yogananda SB, Dheeraj M and Giridhar M

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Abstract
Agriculture has progressed from early food gathering to today's era of precision farming, marked by landmark achievements such as the Green, White and Evergreen Revolutions, each strengthening national food security and productivity. Nevertheless, weeds still reduce crop yields by an estimated 25-30%, and conventional herbicides continue to face significant drawbacks including poor species specificity, herbicide resistance, chemical residues and potential risks to human and animal health. Nanotechnology is the manipulation of matter to a nano scale offers promising solutions. By enabling slow-release and target-specific delivery of herbicides, it reduces the quantity of chemicals required while improving efficacy. This review highlights recent developments in nanotechnology-based weed management, emphasizing nano-encapsulation, smart delivery systems, reduced environmental risks and enhanced crop productivity. Notable examples include encapsulated sulfentrazone, nano-atrazine and paraquat-loaded chitosan nanoparticles, which have shown superior weed suppression, lower phytotoxicity and higher crop yields compared with conventional formulations. Other innovative strategies involve depleting weed seed banks, exhausting carbohydrate reserves in propagules using silver nanoparticles and α-amylase and improving foliar absorption and systemic translocation of active ingredients. These nanotechnology interventions offer key advantages such as reduced chemical usage, lower residue deposition, improved input efficiency and the possibility of recycling magnetic nanocarriers. However, issues including nanoparticle toxicity, challenges and regulatory hurdles underscore the need for careful evaluation and responsible implementation as the field advances.

Keywords: Nanotechnology, weed management, nanoherbicides, smart delivery, encapsulation

Introduction

The global population is projected to grow from over 7 billion to nearly 8.7 billion by 2033, placing considerable pressure on per-capita food supplies (FAO, 2024) [9]. Agriculture, since its beginnings in primitive food gathering, has advanced through successive stages to the current era of precision farming, each step delivering significant benefits to human welfare (Singh, 2012) [27]. Meeting the food requirements of this rising population demands efficient use of natural and renewable resources (Fraceto *et al.*, 2016) [11]. To sustain higher production, farming increasingly depends on external inputs such as fertilizers and pesticides. Among the various constraints, weeds are particularly damaging because they compete aggressively with crops and cause major yield losses. Effective weed management is therefore a crucial agronomic practice. Manual removal is labour-intensive around 320 man-hours are needed per hectare. Herbicides remain the most practical on-farm method, yet in India, where nearly two-thirds of agriculture is rainfed and herbicide use is limited, unchecked weeds can sharply reduce harvests in fragile agro-ecosystems.

Globally, about 4 million tonnes of pesticides are applied each year: roughly 40% herbicides, 30% insecticides and 20% fungicides (Rojas *et al.*, 2022) [26]. While these chemicals boost food production, indiscriminate or excessive application leads to environmental contamination and public-health risks (Dong *et al.*, 2021; Okeke *et al.*, 2021) [8, 22]. Weeds alone account for the greatest share of crop losses among all agricultural pests, with average yield reductions of about 34% (Jabran *et al.*, 2015) [15]. Conventional herbicides also fail to destroy underground propagules such as rhizomes and tubers, which regenerate new infestations in subsequent seasons. Soils carrying weed seeds thus continue to produce lower yields unless weeds are effectively controlled.

Although synthetic herbicides are generally cost-effective, herbicide resistance is an escalating problem (Kumar *et al.*, 2017) [18]. To date, 533 cases of resistance have been recorded in 273 weed species out of these 156 dicots and 117 monocots across 168 different herbicides. The Herbicide Resistance Action Committee (HRAC) groups herbicides into 34 classes based on mode of action, with resistance most frequent in Poaceae (54%), followed by Brassicaceae and Asteraceae (30%) (Oreja *et al.*, 2024) [23].

Nanotechnology offers a promising route to counter these challenges. Nano-enabled herbicides can release active ingredients in a controlled, sustained manner and target weeds precisely, reducing application frequency and slowing the evolution of resistance. Such improvements in herbicide efficacy can ultimately enhance and stabilize crop yields. Nanotechnology refers to manipulating materials at the 1-100 nm scale, where unique physical and chemical properties arise (Campos *et al.*, 2023; Lv *et al.*, 2023) [4, 19]. Its application in agriculture is known as phyto-nanotechnology is gaining momentum for addressing nutrient management, pest and disease control and particularly weed management (Choudhary *et al.*, 2020) [6]. Nanomaterials offer enhanced reactivity, precise targeting, controlled release and superior environmental compatibility, making them well-suited for precision farming. Strategies such as targeted delivery and reduced dosage further support sustainable crop protection (Khan *et al.*, 2024; Gayathri *et al.*, 2023) [16, 12]. This review examines recent advances, underlying mechanisms, current applications and future prospects of nanotechnology in weed management, highlighting its potential to enable efficient and sustainable crop production systems.

Challenges and Issues in Weed Management

Weed management continues to be a major constraint in modern agriculture because of herbicide resistance, the persistence of weed seed banks, environmental contamination and growing labour shortages. Using a single herbicide across a multi-species weed population often leads to poor control and eventually herbicide resistance. When plant communities with only mild herbicide susceptibility are exposed repeatedly one season to a particular herbicide and the next to a different one, resistant biotypes can gradually emerge and become difficult to control with chemicals (Chinnamuthu and Kokiladevi, 2007) [5]. Excessive herbicide applications also leave residues in soil, harming non-target organisms and degrading soil health. Depending on application practices, an estimated ten to seventy-five percent of applied pesticides never reach their intended targets, frequently contaminating terrestrial and aquatic ecosystems (Rojas *et al.*, 2022) [26]. Even herbicides designed to act selectively on weeds can injure crop plants. Moreover, chemical inputs can suppress essential soil biota such as bacteria, fungi, actinomycetes, algae, roots and flagellates that drive humus formation; their decline inevitably lowers the nutritional quality of the soil (Rojas *et al.*, 2022) [26]. Labor shortages and high costs further limit the feasibility of manual or cultural weed control, while organic and genetically modified cropping systems require alternative strategies that avoid synthetic herbicides.

Nanotechnology offers a potential path forward for precision weed management. Nanoherbicides enable controlled, site-specific delivery of active ingredients, improving plant uptake, reducing chemical waste and lowering the risk of environmental pollution. Yet the adoption of this technology faces several obstacles: limited farmer awareness and training, concerns over nanoparticle toxicity, high production costs and the lack of large-scale field validation. Regulatory frameworks for evaluating the safety, environmental impact and permissible residues of nanopesticides also remain underdeveloped in many regions. Research has demonstrated the promise of nano-encapsulated herbicides such as nano-atrazine and paraquat-loaded nanoparticles, which achieve effective weed suppression at lower doses and with reduced residual toxicity (Muchhadiya *et al.*, 2022; Grillo *et al.*, 2014) [21, 13]. Nonetheless, moving from laboratory breakthroughs to field-level adoption will require strong extension programs, interdisciplinary collaboration and supportive policies to ensure that nanotechnology is deployed safely and sustainably in weed management.

Nanoherbicides: Definition and Importance

Nanoherbicides are specially engineered herbicide formulations in which the active ingredients are coated or encapsulated within nanocarrier materials measuring roughly one to one hundred nanometres (Paul *et al.*, 2024) [24]. These nano-enabled products are designed to suppress weeds more efficiently and sustainably than conventional herbicides (Cuenya, 2010) [7]. By embedding herbicidal molecules inside nanoparticles, they gain distinctive features such as larger surface area, greater chemical stability, controlled release and improved target specificity. In contrast to traditional herbicides, which frequently lead to off-target injury, environmental contamination and resistance development but nanoherbicides deliver the active compound precisely, leave less residue and remain effective at lower dosages (Forini *et al.*, 2022) [10]. Their design addresses key limitations of ordinary herbicides, including losses through evaporation, volatilization, leaching, runoff, erosion, photochemical breakdown and both microbial and chemical degradation (An *et al.*, 2022; Paul *et al.*, 2024) [3, 24]. Loading herbicides into nanomaterials with high specific surface area also enhances wettability and dispersibility, allowing the minute active ingredients to spread more effectively (Forini *et al.*, 2022; Manisankar *et al.*, 2022) [10, 20]. To maximize the advantages of nanoherbicides, fabrication efforts focus on refining physicochemical characteristics such as particle size, shape, surface chemistry and concentration, since the chemical composition of the nanocarriers strongly influences how the active ingredients interact with weed foliage, roots and seeds (Forini *et al.*, 2022) [10].

Uptake and Transportation of Nanoherbicides in Plant Systems

The movement of nanoherbicides within plant systems depends on their mode of application, physicochemical properties, and plant anatomy (Forini *et al.*, 2022) [10]. Two principal routes of uptake and transport are:

1. Soil Application (Irrigation-Based)

When applied to the soil, nanoherbicides are absorbed by the plant roots. After crossing the root epidermis, they move either through the apoplastic route, which follows cell walls and intercellular spaces or through the symplastic route, which passes from cell to cell *via* plasmodesmata. Once inside the vascular tissue, the nanoherbicides enter the xylem and are transported upward (acropetally) to the aerial parts of the plant.

2. Foliar Spray Application

When nanoherbicides are sprayed onto leaves, they can enter through stomata, cuticle pores or directly across the epidermis. Once inside the leaf tissue, they move through the symplastic pathway and are translocated via the phloem, enabling basipetal (downward) movement toward the roots. Their uptake is facilitated by mechanisms such as endocytosis, pore formation or carrier proteins, which allow deep penetration and systemic action.

Nanoformulation Synthesis for Weed Management:

The synthesis of nanoformulations for herbicide delivery is a transformative approach in advanced weed management. By manipulating herbicide molecules at the nanoscale, scientists have developed systems that offer targeted action, controlled release and reduced environmental toxicity. Encapsulation of active ingredient (a.i.) is done by Kumar and Chinnamuthu (2020) [6]:

1. Indirect method of nanoencapsulation (IDM)
2. Direct method of nanoencapsulation (DM)

1. Nanoencapsulation of pendimethalin herbicide by direct method

Synthesis of MnCO3 core material: Equal volumes of 0.33 M ammonium bicarbonate (NH_4HCO_3) and 0.33 M manganese sulphate monohydrate ($MnSO_4$) solutions were combined in a round-bottom flask. An equal volume of 0.5% ethanol was then added to the mixture and the solution was vigorously stirred for 10 minutes. It was allowed to stand undisturbed for 10 minutes and subsequently incubated in a water bath at 75 °C for 1 hour. The mixture was centrifuged to sediment the particles, which were then washed three times with distilled water, centrifuging after each wash. The final suspension was filtered through Whatman No. 41 filter paper and the filter paper with the deposited particles was dried in a vacuum desiccator. After drying, the particles were gently scraped off and stored in a vial.

Loading pendimethalin in the MnCO3 core template

Twenty milligrams of $MnCO_3$ core particles were mixed with 25 ml of a 20 ppm pendimethalin solution and gently stirred on a magnetic stirrer for 15 minutes. The suspension was then left to dry overnight, allowing the pendimethalin to adsorb onto the surface of the $MnCO_3$ particles. The dried particles were subsequently collected and stored in a vial.

Encapsulation of pendimethalin adsorbed MnCO3 core material

$MnCO_3$ microcapsules were prepared by sequential (layer-by-layer) adsorption of oppositely charged polyelectrolytes onto $MnCO_3$ microsphere templates. To begin, 20 mg each of poly (allylamine hydrochloride) (PAH) and sodium poly (styrene sulfonate) (PSS) were separately dissolved in 20 ml of 0.5 N NaCl solution. The pH of each solution was adjusted to 6.5-7.0 using hydrochloric acid or sodium hydroxide. Typically, 20 ml of a polyelectrolyte solution was combined with 40 mg of dry $MnCO_3$ microparticles previously adsorbed with pendimethalin, and the suspension was gently stirred on a magnetic stirrer for 15 minutes. It was then centrifuged at 1000 rpm for 15 minutes. The resulting particles were rinsed three times with 0.1 N NaCl to remove unbound material. The same process was repeated using the oppositely charged polyelectrolyte to build alternate layers. Finally, the suspension was centrifuged once more and left to dry overnight. The resulting microcapsules were collected and stored in a vial.

2. Nanoencapsulation of pendimethalin herbicide by indirect method

Preparation of core-shell and hollow-shell particles

Twenty millilitres of the PAH polyelectrolyte solution were mixed with 40 mg of dry $MnCO_3$ microparticles and the suspension was gently stirred on a magnetic stirrer for about 15 minutes. The mixture was then centrifuged at 1000 rpm for 15 minutes and the pellet rinsed three times with 0.1 N NaCl to eliminate any unbound material. The same process was carried out with the oppositely charged PSS solution and alternating PAH and PSS coatings were applied two to three times to build successive layers. Once the desired number of layers was obtained, the $MnCO_3$ core was dissolved by adding 0.1 M HCl and stirring for 15 minutes. The suspension was again centrifuged and washed three times with water before being dried overnight. The resulting hollow-shell particles were collected and stored in a vial.

Loading of pendimethalin in hollow-shell

Twenty milligrams of the prepared hollow-shell particles were mixed with 25 ml of a 20 ppm pendimethalin solution and gently stirred on a magnetic stirrer for 15 minutes. The suspension was then left to dry overnight, after which the pendimethalin-loaded particles were collected and stored in a vial.

Interventions in Weed Management

1. Smart Delivery Mechanisms

Developing a target-specific herbicide molecule encapsulated within nanoparticles aims to deliver the active ingredient directly to receptors in the roots of target weeds. Once absorbed, it is translocated to specific plant parts where it inhibits glycolysis, disrupting the breakdown of stored food reserves. As a result, the weed is effectively starved and eventually dies (Itodo, 2019) [14]. Nanotechnology enables the targeted delivery of herbicides, reducing environmental losses while enhancing their effectiveness. Nanocarriers facilitate site-specific release, ensuring that herbicides are activated only in response to specific biochemical signals within weed root systems. For example, nanoencapsulation techniques have successfully delivered active ingredients directly to receptors in the root zone, where they disrupt glycolysis and ultimately starve weeds to death. In addition, nano-surfactants such as those derived from soybean micelles have been shown to reverse glyphosate resistance in crops and improve herbicide absorption (Adarsh *et al.*, 2024) [1].

2. Depleting the Weed Seed Bank

Traditional methods such as the stale seedbed technique can help reduce the weed seed bank but are often labor and resource-intensive. Nanotechnology offers innovative alternatives by disrupting seed viability and germination patterns, thereby lowering weed emergence. Smart-release nanoformulations can maintain herbicidal activity for extended periods, effectively suppressing seedlings as they emerge from the seed bank (Adarsh *et al.*, 2024) [1].

Nanoencapsulation of atrazine significantly increased the mortality of *Bidens pilosa* seedlings, even when applied at a tenfold dilution. Encapsulation also reduced the long-term residual effect of the herbicide, likely by decreasing atrazine mobility in the soil, which in turn increased herbicide availability for seedlings (Preisler *et al.*, 2020) [25]. The nanoformulation showed enhanced herbicidal activity against *Brassica* species as well, resulting in 100% mortality and greater overall effectiveness.

3. Exhausting Food Reserves in Weeds

Silver nanoparticles (AgNPs), in combination with enzymes like α-amylase, have proven effective in reducing starch content in weed propagules. In *Cyperus rotundus*, treatments involving α-amylase and AgNPs significantly lowered starch concentration from 131.4 mg/g in the control to 98.14 mg/g at the highest treatment level indicating a reduction in energy reserves essential for regrowth (Viji and Chinnamuthu, 2015) [30]. Atrazine-loaded polycaprolactone (PCL) nanocapsules offer a controlled-release strategy for post-emergent weed control. In greenhouse studies, nano-atrazine significantly inhibited biomass accumulation and induced oxidative stress in *Bidens pilosa* and *Amaranthus viridis* compared to conventional formulations (Sousa *et al.*, 2018) [28]. The improved efficacy is attributed to enhanced foliar uptake and sustained herbicidal action.

4. Season-Long Weed Control with Slow-Release Formulations

Nanoformulations help prevent uncontrolled release and premature degradation of herbicides by incorporating three key features: encapsulation materials that enable slow, controlled release; antimicrobial components that limit microbial breakdown; and capping agents that protect the formulation from environmental stresses (Adarsh *et al.*, 2024) [1]. Encapsulating paraquat within nanoparticle polymeric matrices results in a delayed release compared to the free herbicide, with only 70% released under laboratory conditions versus 92% for the unencapsulated form. In field conditions, release is further slowed due to factors such as low humidity and interactions with soil organic matter (Grillo *et al.*, 2014) [13].

5. Enhanced Foliar Absorption and translocation

Nanoparticles improve herbicide penetration through the leaf cuticle by lowering droplet surface tension, enhancing diffusion across lipid barriers and facilitating the conversion of active ingredients into ionic forms that can pass through cutin and pectin layers (Adarsh *et al.*, 2024) [1]. These effects result in better spreadability and uptake, ensuring that the herbicide efficiently reaches internal target sites.

Because of their nanoscale size and specialized formulation, nanoherbicides demonstrate enhanced translocation within plants. They move acropetally (upward through the xylem) to reach upper plant tissues and basipetally (downward through the phloem), with glucose-nanoparticle conjugation further promoting systemic distribution (Adarsh *et al.*, 2024) [1]. In radiolabeled studies, nanoatrazine (nanoATZ) exhibited faster absorption and greater systemic movement than conventional atrazine, leading to stronger Photosystem II (PSII) inhibition and more effective weed control (Takeshita *et al.*, 2021) [29].

Challenges for nanotechnology application in weed management

The major challenge in adopting this technology on a large scale is managing the associated risks. As the saying goes, *"technology—yes, but safety—must,"* it is essential to carefully evaluate the possible risks and consequences of using nanoparticles before large-scale implementation. Key concerns include the limited market progress of agricultural nanotechnology due to low cargo-loading capacity, the unpredictable behavior and potential toxicity of nanoparticles, insufficient research on their long-term effects and the need to address production costs, evaluation standards, registration policies and public concerns (Kumar and Chinnamuthu, 2020) [6].

Toxicity of Nanomaterials

When humans are exposed to nanoherbicides, the tiny nanoparticles can enter the body through inhalation, ingestion, skin contact or injection. These particles can reach different organs, including the brain, lungs, heart, liver and kidneys, potentially leading to health problems. They may cause lung diseases like asthma, brain disorders like Alzheimer's, heart issues and even skin allergies. Long-term exposure could lead to serious conditions, depending on how much and how often a person is exposed. Nanomaterial toxicity may be influenced by the starting material composition, structure, size, shape, surface characteristics, agglomeration, purity. Therefore, it is important to investigate/predict the toxicity of any new nanomaterial and propose limitation strategies (Ahmed *et al.*, 2022) [2].

Future Line of Work

Nanotechnology is therefore regarded as a potential boon for achieving targeted inhibition of the biochemical processes in weeds. However, the science is still in its early stages. Future research must focus on developing delivery systems that can improve the release profile of herbicides without altering their properties, along with creating novel carriers that enhance herbicidal activity while minimizing environmental impact. The long-term hazards associated with the continuous use of nanoparticles remain largely unknown. Hence, comprehensive research and development are essential to refine this technology and enable its safe and effective use.

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Competing Interests

Authors have declared that no competing interests exist.

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