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Evaluating the Potential of Nano-Based Herbicides in the Control of Invasive Weed Species

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ABSTRACT: Invasive weed species pose a significant threat to global agriculture, contributing to substantial yield losses, ecological disruption, and economic burdens. Conventional herbicide use, though central to weed management, is increasingly constrained by herbicide resistance, environmental contamination, and non-target toxicity. Nano-based herbicides (nanoherbicides) have emerged as a promising alternative, offering controlled release, enhanced foliar adhesion, and improved bioavailability of active ingredients. This review critically evaluates the development, synthesis, and encapsulation strategies of nanoherbicides, highlighting their novel modes of action, comparative efficacy against invasive weeds, and potential to reduce chemical loads while maintaining crop safety. Case studies demonstrate improved performance of nanoformulations at reduced application rates, sustained field activity, and decreased risk of resistance development. However, uncertainties remain regarding their long-term environmental fate, potential toxicity to non-target organisms, and the absence of nanoparticle-specific regulatory frameworks. Future prospects lie in the design of biodegradable nanocarriers, integration with precision agriculture, genome-targeted delivery systems, and multifunctional nano-formulations combining weed control with nutrient management. The adoption of nanoherbicides, guided by robust risk assessment and interdisciplinary research, could provide a transformative pathway toward sustainable and resilient weed management in modern agriculture.

KEYWORDS: biodegradable nanocarriers; environmental safety; herbicide resistance; invasive weed species; nanoherbicides; precision agriculture; sustainable agriculture

1. INTRODUCTION

The global agricultural sector faces an escalating threat from invasive weed species, which undermine crop productivity, disrupt ecosystems, and impose severe economic burdens. Invasive weeds such as *Amaranthus palmeri* and *Tithonia diversifolia* aggressively outcompete crops for vital resources like water, light, and nutrients, leading to significant yield losses. Current estimates suggest that invasive weeds contribute to an annual 31.5% reduction in agricultural production globally, translating into economic losses exceeding USD 32 billion (Kubiak et al., 2022).

Beyond direct crop losses, invasive weeds also inflict broad ecological consequences. Their spread alters ecosystem functions, diminishes biodiversity, and degrades natural resources including soil and water (Mayfield et al., 2021; Funk et al., 2014). In vulnerable agroecosystems, climate change further exacerbates these dynamics by accelerating the adaptability and spread of invasive species, compounding management challenges (Clements et al., 2014). The need for globally coordinated responses is underscored by the transboundary nature of weed invasions and their profound impacts on food security, particularly in developing regions (Paini et al., 2016; Joshi & Matthews, 2023).

Conventional herbicides remain the principal tool in weed management, yet their effectiveness is increasingly compromised. Globally, more than 480 cases of herbicide-resistant weed species have been documented, affecting at least 252 plant species (Pallett, 2023). Repeated use of chemical herbicides accelerates resistance development, often forcing farmers into a "pesticide treadmill" where newer, more potent chemicals are required with diminishing returns. Moreover, these herbicides contribute to environmental degradation through soil and water contamination, toxicity to non-target species, and disruption of soil biodiversity (Hasanuzzaman et al., 2020; Abbas et al., 2018).

In light of these challenges, nanotechnology has emerged as a novel and promising alternative for sustainable weed control. Nano-based herbicides, or nanoherbicides, involve the encapsulation or delivery of active herbicidal ingredients through nanoparticles, enabling controlled release, improved foliar adhesion, and increased bioavailability (Zargar et al., 2023; Zhou et al., 2023). Such systems can reduce application dosages, limit environmental exposure, and overcome resistance mechanisms by targeting specific physiological or molecular pathways in weeds (Bayat et al., 2023). For instance, poly(ε-caprolactone) (PCL)-based nano-formulations have demonstrated extended released properties, biodegradability, and enhanced efficacy against resistant weed populations (Takeshita et al., 2022a).

Despite these advances, the integration of nanoherbicides into mainstream agricultural practice remains limited. Regulatory uncertainties, knowledge gaps in environmental interactions, and scalability concerns must be addressed. Current literature underscores the need for multidisciplinary research combining agronomy, nanoscience, and environmental toxicology to unlock the full potential of nano-enabled weed management (Zargar et al., 2023).

This review explores the current status, innovations, and future directions in the use of nano-based herbicides for controlling invasive weed species, with an emphasis on their effectiveness, environmental safety, and practical applicability in modern agriculture.

1.2 Purpose and Scope of the Review

The primary purpose of this literature review is to critically examine the potential of nano-based herbicides as an innovative approach to managing invasive weed species in agricultural systems. Given the limitations of conventional herbicides including the accelerating emergence of resistant weed populations, environmental contamination, and off-target toxicity nano-herbicides represent a promising technological advancement. This review aims to consolidate current scientific knowledge on their development, formulation, modes of action, and field performance, while also addressing the environmental, safety, and regulatory considerations that influence their adoption.

The scope of the review spans three core dimensions: (i) the technological foundations of nano-herbicide synthesis, encapsulation, and delivery systems; (ii) their comparative effectiveness against common invasive weed species in relation to conventional herbicide formulations; and (iii) the broader ecological and socio-economic implications of their deployment (Table 1). The review also highlights key invasive weeds of global agricultural concern, outlines the biological and management challenges they pose, and situates nano-herbicides within integrated weed management frameworks. By integrating findings from agronomy, nanotechnology, and environmental sciences, the review seeks to identify both the opportunities and the constraints associated with the adoption of nano-based weed control strategies, thereby providing a foundation for future research, policy formulation, and sustainable agricultural practices.

Table 1. Global economic impact of invasive weeds on agriculture

Region	Estimated yield loss %	Economic loss USD billion/year	Example major invasive weeds
North America	12–20	4.2	amaranthus palmeri, ambrosia artemisiifolia
South America	15–25	3.8	eichhornia crassipes, brachiaria spp.
Europe	10–18	2.5	ambrosia artemisiifolia, fallopia japonica
Sub-Saharan Africa	25–40	9.1	striga hermonthica, parthenium hysterophorus
North Africa & Middle East	20–30	3.0	orobanche spp., cyperus rotundus
South Asia	22–35	5.4	parthenium hysterophorus, lantana camara
Southeast Asia	18–28	2.7	chromolaena odorata, mimosa pigra
Australia & Pacific	12–22	1.5	parthenium hysterophorus, opuntia stricta
Global Total	—	32.2	—

Source: Kubiak et al., 2022; Joshi & Matthews, 2023

2. OVERVIEW OF NANOTECHNOLOGY IN AGRICULTURE

2.1 Definition and Types of Nanomaterials

Nanotechnology, defined as the manipulation of materials at the nanoscale (1–100 nm), offers unique physicochemical properties such as high surface area, reactivity, and controlled release behavior that are distinct from their bulk counterparts (Darbre, 2023). In agriculture, these characteristics make nanomaterials suitable for targeted delivery of agrochemicals, enhanced nutrient uptake, and environmental monitoring.

Nanomaterials are broadly classified into organic and inorganic types. Organic nanoparticles, including lipid-based and polymeric nanoparticles, are primarily used for controlled release systems and biocompatible delivery of growth stimulants or protective agents (Khan et al., 2024). Inorganic nanoparticles encompass materials like silver (AgNPs), valued for their antimicrobial properties, and silica nanoparticles (SiO_2), which are used for their structural stability and utility in both agricultural and cosmetic applications (Karadbhajne et al., 2024).

Other relevant types include chitosan nanoparticles, which are biodegradable and enhance plant resilience under abiotic stress conditions, and nano-clays, which improve the mechanical properties of soils and composites (Mokhena et al., 2020) (Table 2).

Table 2. Comparative properties of nanomaterials used in agriculture

Nanomaterial type	Particle size nm	Biodegradability	Primary agricultural applications	Advantages	Potential limitations/toxicity concerns
Polymeric nanoparticles (e.g., PLGA, PCL, starch-based)	50–300	High	Controlled herbicide release, nutrient delivery	Biocompatible, sustained release, reduced leaching	May require complex synthesis; cost considerations
Lipid-based nanoparticles (e.g., liposomes, solid lipid NPs)	50–200	High	Encapsulation of hydrophobic herbicides/pesticides	High loading efficiency, safe degradation products	Stability issues under high temperatures
Chitosan nanoparticles	20–250	High	Herbicide carriers, plant stress mitigation	Antimicrobial properties, pH-responsive release	Possible allergenicity; variability in degradation rate
Silica nanoparticles (SiO_2)	10–200	Low	Structural carrier, slow-release formulations	High stability, large surface area	Persistence in soil; potential respiratory hazard in production
Silver nanoparticles (AgNPs)	1–100	Low	Antimicrobial and antifungal applications	Strong antimicrobial activity	Risk of soil microbiome disruption; bioaccumulation concerns
Nano-clays (e.g., montmorillonite, kaolinite)	30–200	Moderate	Soil conditioning, slow-release carriers	Improve soil structure, inexpensive	May immobilize nutrients; limited biodegradation
Metal oxide nanoparticles (e.g., ZnO, TiO_2)	10–150	Low–Moderate	Micronutrient delivery, antimicrobial action	Enhanced nutrient uptake, UV protection	Potential toxicity to aquatic life; oxidative stress risks

Source: García-Gómez et al., 2023; Jampílek & Kráľová, 2015

2.2 Mechanisms of Action in Agriculture

The application of nanotechnology in agriculture is grounded in three key mechanisms: controlled release, targeted delivery, and enhanced solubility and uptake. Controlled release systems utilize nanocarriers to encapsulate agrochemicals, allowing for gradual, sustained delivery of active ingredients. This minimizes environmental runoff, reduces the frequency of applications, and ensures more consistent nutrient availability throughout crop growth stages (Nizamani et al., 2024; Padhan et al., 2023).

Targeted delivery systems direct agrochemicals precisely to pest-infested areas or nutrient-deficient plant tissues. Functionalized nanoparticles can be engineered to respond to pH, enzymes, or environmental triggers, releasing their payloads only under specific conditions. This specificity significantly reduces off-target effects and environmental contamination (Rathore et al., 2024).

Enhanced solubility and uptake is another advantage of nanoscale materials. Nutrients that are poorly soluble in water, such as zinc or iron, become more bioavailable when delivered through nanoparticles. These particles facilitate absorption through plant stomata, root hairs, and cell membranes, improving nutrient translocation and plant health (Sharma et al., 2024).

While these mechanisms collectively contribute to increased efficiency, reduced chemical use, and better crop productivity, they also raise important questions about potential toxicity to non-target organisms and bioaccumulation in ecosystems. Continued investigation into their safety, lifecycle, and regulatory oversight remains critical for sustainable application (Mohapatra et al., 2024).

3. NANO-HERBICIDES

3.1 Development and Formulation of Nano-Herbicides

The development of nano-herbicides represents a strategic shift toward sustainable weed management by overcoming the limitations of conventional chemical herbicides. These nano-formulations are engineered to reduce application volumes while enhancing selectivity and efficiency against target weeds (Jayasoorya & Kumar, 2024).

One of the central advantages lies in their controlled release mechanisms, which allow for the gradual and sustained delivery of active ingredients. This not only prolongs the herbicidal effect but also reduces the frequency of application and mitigates environmental contamination (Zhao et al., 2018). Furthermore, biodegradable carriers such as chitosan, clay, and other plant-based materials are used to encapsulate active ingredients, supporting eco-friendly degradation and reducing residues in soil and water (Tosco et al., 2024).

In addition to their environmental benefits, nano-herbicides contribute to weed seed bank depletion through innovative approaches like damaging reproductive structures, such as pollen grains, leading to long-term weed suppression (Shanker et al., 2024). Despite their potential, there are still unresolved concerns about their long-term fate in ecosystems and interactions with non-target organisms. Addressing these gaps through long-term field trials and environmental impact studies remains a critical research priority.

3.2 Synthesis and Encapsulation of Nano-Herbicides

The synthesis of nano-herbicides often relies on encapsulating conventional herbicides such as glyphosate and atrazine within nanoscale carriers, enhancing their solubility, bioavailability, and weed control efficacy. Polymer-based carriers like chitosan, zein, and lignin are commonly used due to their biocompatibility and ability to modulate the release of herbicides (Munhoz-Garcia et al., 2025). These systems, such as the ZN-PL (zein-lignin) complex, have demonstrated up to 96% weed control efficacy while exhibiting low toxicity to non-target crops and soil biota.

In terms of carrier design, nanocapsules, nanospheres, and mesoporous silica nanoparticles have proven to be effective for site-specific delivery and increased stability under field conditions. Additionally, green synthesis techniques using plant extracts, microbes, or fungi offer a sustainable alternative to conventional chemical methods, significantly reducing the environmental toxicity associated with herbicide production (Souza et al., 2019; Susha et al., 2022).

Although these advancements in synthesis offer promising outcomes, a significant research gap persists in the standardization of synthesis protocols, especially in optimizing particle size, stability, and environmental compatibility. More studies are also needed to evaluate field-level efficacy and cost-effectiveness of these formulations (see Table 3).

Table 3. Nano-herbicide formulations

Active Ingredient	Nanocarrier Type	Particle Size (nm)	Release Characteristics	Target Weed Species	Reported Efficacy (%)	Notes / Advantages
Metribuzin	Poly(ε-caprolactone) (PCL) nanocapsules	120–150	Controlled, sustained release (~10–20 days)	Amaranthus palmeri	90–95	Biodegradable carrier; reduced leaching and prolonged activity
Glyphosate	Chitosan nanoparticles	80–120	pH-responsive release; foliar adhesion	Parthenium hysterophorus	~85–90	Improved foliar uptake; biodegradable; potential crop safety
Atrazine	Zein–lignin (ZN-PL) complex (polymeric matrix)	100–140	UV-protected, sustained release	Chromolaena odorata	~95–96	High encapsulation efficiency; lower non-target toxicity reported
Diuron	Mesoporous silica nanoparticles (MSNs)	60–100	Slow release (micro-to-days scale)	Striga spp. / Striga hermonthica	~90–92	High stability & tunable pore size for release control
Imazapic	Clay-based nanocarrier (e.g., montmorillonite)	150–200	Moisture-triggered / slow release	Lantana camara	~80–86	Low cost; good soil retention; moderate biodegradability
Tebuconazole (used synergistically)	Green-synthesized AgNPs (bio-reduced)	20–50	Fast uptake; short-term action	Aquatic weeds (e.g., Eichhornia crassipes)	~88–90	Antimicrobial boost; rapid activity but persistence concerns
Metribuzin	Polymeric nanosphere (PLGA/zein variant)	80–130	Pulsed/controlled release, photostable	Mixed broadleaf weeds	85–93	Enhanced photostability and target penetration
Generic herbicide (e.g., various a.i.)	Lipid-based nanoparticles (liposomes / SLNs)	50–200	Rapid release or tunable sustained release	Various invasive weeds	Variable (70–92)	Good for hydrophobic actives; high loading efficiency

Source: Wang et al., 2022; Itodo, 2019; Tosco et al., 2024

3.3 Modes of Action in Weed Control

Nano-herbicides introduce novel modes of action that distinguish them from conventional herbicides, primarily through their enhanced penetration, site-specific targeting, and environmental stability. Their nanoscale size enables them to efficiently penetrate plant cuticles and cell walls, facilitating deeper and more effective delivery of active ingredients (Zargar et al., 2023; Forini et al., 2022).

Once inside plant tissues, these formulations can be designed for controlled and localized action, allowing for disruption of specific physiological processes such as photosynthesis, cell division, or root elongation (Amna et al., 2019). This precision significantly reduces off-target effects and lowers the risk of herbicide resistance.

Moreover, nano-herbicides are less prone to leaching and volatilization, two common pathways of environmental contamination. The encapsulation in biodegradable matrices ensures that the active compounds remain stable, release slowly, and degrade safely over time (Takeshita et al., 2024). These attributes contribute to enhanced weed control while protecting surrounding ecosystems.

Nevertheless, there is still a limited understanding of long-term environmental impacts, especially concerning accumulation in soil and interactions with microbial communities (Figure 1). Future research should prioritize ecotoxicological evaluations, particularly under diverse agroecological conditions.

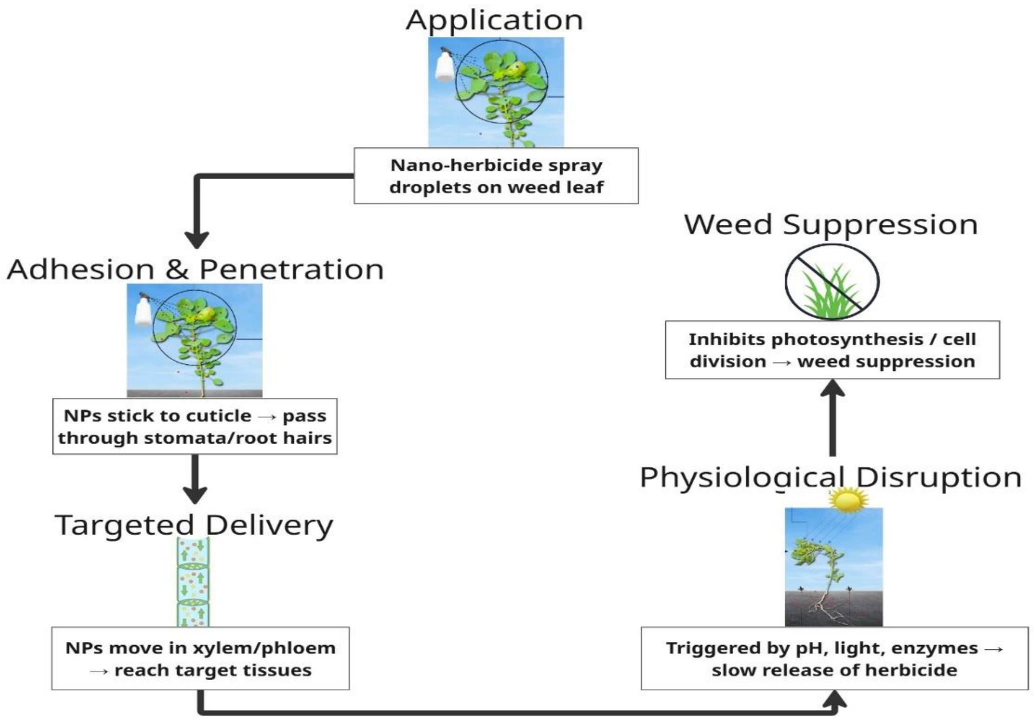

Figure 1. Schematic representation of the mode-of-action pathway for nano-herbicides, from application to targeted weed suppression (Adapted from Zargar et al., 2023; Forini et al., 2022; Shanker et al., 2024).

4. INVASIVE WEED SPECIES

4.1 Common Invasive Weeds in Croplands

Invasive weeds are among the most serious biotic threats to global agriculture, particularly in tropical and subtropical regions (Roberts et al., 2022 & 2024). Their rapid spread and resilience in disturbed habitats have led to severe impacts on crop productivity, biodiversity, and ecosystem stability. Certain species have become especially notorious for their adaptability, competitiveness, and resistance to conventional control methods.

Parthenium hysterophorus, a highly aggressive annual weed, has been ranked among the world's most invasive plant species. It affects a wide range of crops in over 45 countries, largely due to its prolific seed production (up to 25,000 seeds per plant), drought tolerance, and potent allelopathic effects, which inhibit the germination and growth of neighboring plants. These traits not only reduce crop yields dramatically up to 81% in sorghum fields but also hinder the establishment of native vegetation (Bajwa et al., 2020; Masum et al., 2012).

Chromolaena odorata is another formidable invasive weed, particularly in tropical Asia and Africa. Known for its vigorous vegetative growth and chemical interference with crop physiology, it hampers seed germination and seedling establishment in maize, soybean, and other economically important crops. Its aggressive colonization, high fecundity, and resistance to common herbicides have made it a persistent problem in many agricultural systems (Raj & Syriac, 2016).

Striga spp., including *Striga hermonthica* and *Striga asiatica*, are parasitic weeds that inflict significant damage on cereal crops such as maize, sorghum, and millet. These root-attaching parasites siphon off nutrients and water, often leading to total crop failure, especially under low-fertility conditions. In Africa alone, Striga infestations are responsible for billions of dollars in agricultural losses annually (Raj & Syriac, 2016).

Lantana camara, originally introduced as an ornamental plant, has now invaded millions of hectares of agricultural and forested lands. Its toxic foliage deters grazing, while its dense thickets suppress understory vegetation and displace native flora. The species also alters fire regimes and contributes to land degradation, complicating land management efforts and biodiversity conservation (Raj & Syriac, 2016).

The persistence of these species is tied to their biological advantages: high seed viability, rapid reproductive cycles, and adaptability to varied environments. Their dominance in croplands demands robust, science-driven management strategies that go beyond conventional herbicide use and include ecological and technological innovations (Figure 2).

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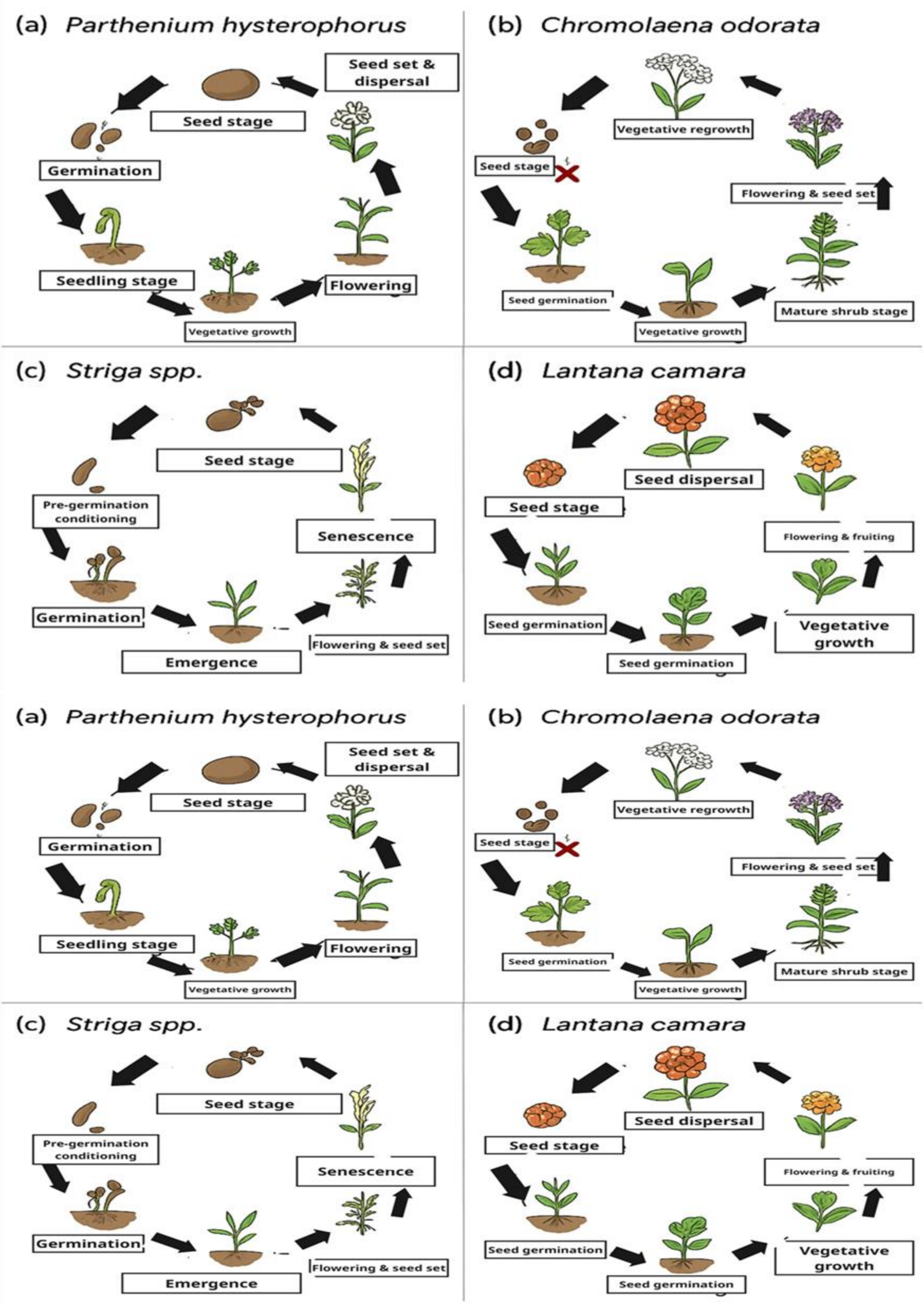

Figure 2. Lifecycle diagrams of four major invasive weed species in croplands: (a) Parthenium hysterophorus, (b) Chromolaena odorata, (c) Striga spp., and (d) Lantana camara. Arrows indicate transitions between growth stages. Red symbols mark potential intervention points for nano-herbicide application (Masum et al., 2012; Raj & Syriac, 2016).

4.2 Challenges in Managing Invasive Species

The management of invasive weeds in agricultural landscapes presents a multi-dimensional challenge, largely due to the ecological flexibility, reproductive vigor, and evolving resistance mechanisms of these species. These biological features, combined with environmental and socio-economic constraints, hinder the success of traditional weed control strategies.

A key obstacle is the extraordinary adaptability and fecundity of invasive weeds. For instance, Amaranthus palmeri (Palmer amaranth), a rapidly spreading C4 weed, exhibits both high plasticity and prolific seed production up to 600,000 seeds per plant. Its fast growth and ability to thrive under diverse environmental conditions enable it to outcompete crops and evade standard management approaches. Moreover, many invasive species display phenotypic plasticity, adjusting their growth and reproduction in response to different ecological pressures.

Another growing concern is the global rise in herbicide resistance. As of 2023, at least 267 weed species have evolved resistance to one or more herbicide modes of action (Kumar et al., 2023). Resistance mechanisms such as target site mutations and enhanced metabolic detoxification (non-target site resistance) reduce herbicide efficacy and force farmers into reliance on higher doses or alternative chemicals—practices that are both economically and environmentally unsustainable.

Additionally, invasive weeds often establish dominance in disturbed ecosystems, particularly those suffering from overgrazing, intensive monocropping, or climate-induced degradation. These weeds alter soil properties, disrupt nutrient cycling, and displace beneficial microbial communities, making ecosystem recovery more difficult (Monaco, 2012). For example, fire-promoting weeds like *Lantana camara* and *Chromolaena odorata* increase fire frequency and intensity, which further facilitates their spread and suppresses native regeneration.

Climate change intensifies these challenges. Shifting rainfall patterns, temperature regimes, and CO_2 concentrations may enhance the invasiveness and geographic range of many species. Studies show that warming conditions can accelerate seedling development, expand suitable habitats, and extend growing seasons, all of which improve the competitive advantage of invasive species (Colberg et al., 2024).

Notably, secondary invasions where removal of one invader facilitates colonization by another—complicate restoration efforts. This phenomenon underscores the need for holistic, ecosystem-based management rather than single-species suppression. Strategies must include early detection and rapid response systems, community participation, long-term monitoring, and integration of chemical, biological, and cultural control methods (Tataridas et al., 2022).

4.3 Effectiveness of Nano-based Herbicides on Invasive Weeds

The application of nanotechnology in herbicide formulations has introduced significant improvements in the management of invasive weeds. Nano-based herbicides enhance delivery efficiency, reduce environmental impact, and offer potential solutions to herbicide resistance. Their small particle size, large surface area, and controlled-release capabilities enable better penetration and targeted action on weed tissues, thereby improving efficacy compared to conventional herbicides. The following subsections examine comparative studies, performance at low concentrations, long-term persistence in soil, and crop safety.

4.3.1 Studies comparing nano-herbicides vs. conventional formulations

Comparative research indicates that nano-herbicides can outperform traditional formulations in weed suppression. Wang et al. (2022) reported a 31.5% increase in efficacy against target invasive weeds compared to conventional herbicides. Similarly, nanoencapsulated metribuzin achieved effective weed control at doses as low as 48 g a.i. ha^{-1}, a substantial reduction from standard application rates (Takeshita et al., 2022b). Controlled-release nano-formulations minimize premature degradation and volatilization, prolonging herbicide activity in the field (Itodo, 2019) (Table 4). These performance improvements suggest that nano-based formulations can maintain or enhance control efficiency while using smaller quantities of active ingredients (Figure 3).

Table 4. Comparative efficacy of nano-herbicides vs. conventional formulations

Active Ingredient	Formulation Type	Application Rate (g a.i. ha^{-1})	Target Weed Species	Weed Control Efficacy (%)	Environmental Residue / Persistence	Notes on Crop Safety
Metribuzin	Nanoencapsulated (PCL)	48	*Amaranthus palmeri*	~90–92	Controlled release up to 15 days; reduced volatilization	No phytotoxicity reported at tested rates
Metribuzin	Conventional	96	*Amaranthus palmeri*	~88	Faster degradation; higher leaching potential	Minimal crop injury at label rate
Glyphosate	Chitosan nanoparticle	250	*Parthenium hysterophorus*	~85–88	Lower runoff losses; pH-responsive release	Selective, safe for crops tested
Glyphosate	Conventional	500	*Parthenium hysterophorus*	~80–82	Higher runoff potential; no slow-release	Some off-target effects reported
Atrazine	Zein–lignin (ZN-PL) nanoformulation	75	*Chromolaena odorata*	~95–96	UV-protected, slow release	Low toxicity to non-target crops
Atrazine	Conventional	200	*Chromolaena odorata*	~90–91	Moderate persistence; some photodegradation	No crop injury at tested rate
Imazapic	Clay-based nanocarrier	50	*Lantana camara*	~80–83	Moisture-triggered release; reduced leaching	No visible crop stress

Imazapic	Conventional	100	*Lantana camara*	~75–77	Faster degradation; possible leaching	Crop-safe at recommended rates
Tebuconazole (herbicidal synergy)	Green-synthesized AgNPs	30	*Eichhornia crassipes*	~88–90	Rapid uptake; some persistence in sediment	No crop-related issues (aquatic application)

Source: Takeshita et al., 2022a, Jayasoorya & Kumar, 2024, Tosco et al., 2024, Susha et al., 2022

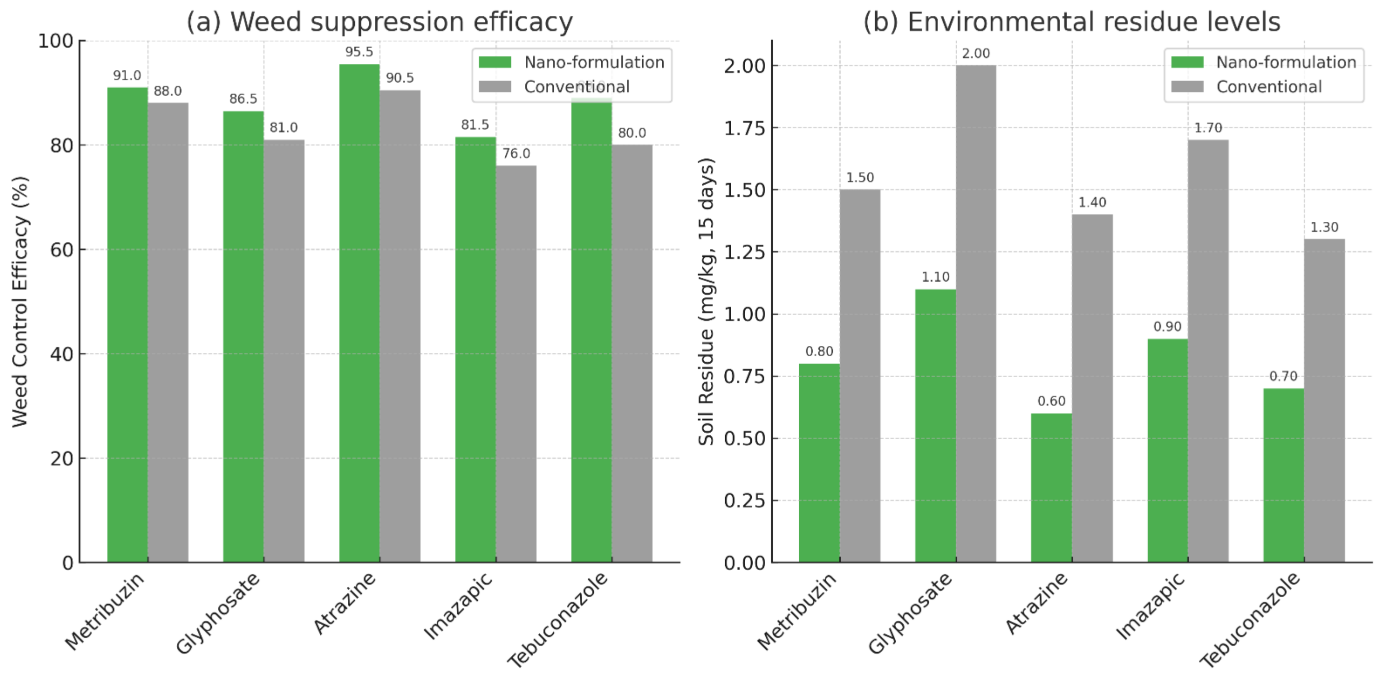

Figure 3. Comparative performance of nano-based vs. conventional herbicide formulations. (a) Weed suppression efficacy (% control) from greenhouse and field trials. (b) Environmental residue levels in soil 15 days post-application. Data adapted from Takeshita et al., 2022a; Munhoz-Garcia et al., 2025; Tosco et al., 2024.

4.3.2 Efficiency in low concentrations

Nano-herbicides exhibit high bioavailability, ensuring that even reduced concentrations deliver effective control. Encapsulation technologies protect active compounds from photodegradation and hydrolysis, enabling sustained action over time (Amna et al., 2019; Iacona et al., 2025). The enhanced penetration into plant tissues due to nanoparticle size improves the delivery of herbicides to their specific sites of action (Forini et al., 2022). This efficiency at low doses reduces chemical load on the environment while maintaining weed suppression performance.

4.3.3 Long-term control and persistence in soil

The persistence and long-term weed control effects of nano-herbicides are influenced by their formulation chemistry, soil interactions, and microbial dynamics. Controlled-release polymers, such as poly(ε-caprolactone), enable extended herbicide activity and reduced application frequency (Zargar et al., 2023). Enhanced resistance to degradation from UV light and microbial breakdown increases the persistence of active ingredients in soil. However, the interaction of nano-formulations with soil organic matter and minerals can affect mobility and bioavailability (Firdaus et al., 2018; Blasioli et al., 2010). Indigenous microbial communities contribute to biodegradation, potentially mitigating long-term accumulation but also risking disruption to soil ecology (Ahmad et al., 2023; Mishra et al., 2021). These dynamics underscore the need for careful formulation to balance efficacy and environmental safety.

4.4 Crop Safety and Selectivity

Nano-herbicides are engineered for improved selectivity, delivering active compounds to target weeds while minimizing crop exposure. Targeted delivery systems reduce off-target effects and residue accumulation in soil and water (Khan et al., 2023). The use of biodegradable carriers such as chitosan further enhances environmental safety and promotes sustainable use. Reduced herbicide doses and lower toxicity reported as up to 43.1% less harmful to non-target organisms (Wang et al., 2022) support crop safety and ecosystem protection. Nonetheless, while these benefits are promising, the rapid adoption of nano-herbicides should be accompanied by thorough long-term ecological risk assessments (Forini et al., 2022).

4.4.1 Nano-herbicide degradation and persistence in the environment

The environmental fate of nano-herbicides is influenced by their physicochemical properties, soil characteristics, and environmental conditions. Factors such as acid/base dissociation constants (pKa), octanol–water partition coefficient (Kow), and water solubility (Sw) affect mobility, sorption, and degradation rates ("Influence of Herbicide Environmental Behavior on Weed Management," 2022). Sorption–desorption hysteresis can prolong persistence in soils by limiting bioavailability and slowing microbial degradation (Sims, 2014).

Soil texture, pH, and organic matter content also play a critical role in nano-herbicide retention and breakdown. Higher organic matter typically enhances sorption, reducing leaching but potentially increasing persistence (Hong, 2006). Environmental conditions such as soil moisture and temperature influence microbial activity, while light exposure can drive photodegradation (Hong, 2006). However, nanoparticles may undergo aging and transformation processes in soil and water, altering both their reactivity and toxicity (Schaumann, 2014). Under certain conditions, this can result in unexpected persistence and possible accumulation in environmental compartments.

4.4.2 Potential Toxicity to Non-target Organisms

While nano-herbicides can reduce chemical loading compared to conventional formulations, their unique properties can also heighten ecotoxicological risks. Studies have shown that nanoparticles such as zinc oxide (ZnO) and titanium dioxide (TiO_2) can significantly reduce soil microbial diversity and activity, impairing nutrient cycling and soil health (García-Gómez et al., 2023; Vijayaraj et al., 2018). In some cases, nanoformulations exhibit higher toxicity than conventional herbicides; for example, nano-tebuconazole demonstrated increased toxicity to the nematode *Caenorhabditis elegans* (Eghbalinejad et al., 2024).

In aquatic systems, metal oxide nanoparticles have been linked to oxidative stress in algae and crustaceans, with potential for trophic transfer to higher organisms including fish and terrestrial wildlife (Jampílek & Králľová, 2024) (Table 5). Such effects could disrupt ecosystem functioning and biodiversity if nanoparticle residues accumulate in water bodies.

Table 5. Summary of ecotoxicity findings for nano-herbicides and nanomaterials

Nanoparticle / Nanoformulation	Test Organism / Non-target Species	Exposure Route & Concentration (typical)	Observed Effects
ZnO NPs (metal oxide)	Soil microbial communities (bacteria, fungi)	Soil exposure; mg kg^{-1} range (laboratory)	Reduced microbial diversity and activity; altered nutrient cycling
TiO_2 NPs (metal oxide)	Freshwater algae (e.g., *Chlorella* spp.), daphnia	Aqueous exposures; µg–mg L^{-1}	Oxidative stress, growth inhibition; impaired photosynthesis
AgNPs (silver nanoparticles)	Soil microbes; nematodes (*C. elegans*); aquatic invertebrates	Soil or water exposures; low µg L^{-1} to mg L^{-1}	Strong antimicrobial action; reduced soil respiration; nematode toxicity; potential trophic transfer
Chitosan NPs (biopolymer carriers)	Beneficial soil microbes, earthworms	Soil application; experimental ranges mg kg^{-1}	Generally low toxicity; can be antimicrobial at high doses; variable effects by formulation
Polymeric carriers (PCL/PLGA nanocapsules)	Soil microbes, non-target plants	Soil/foliar exposure; application-rate dependent	Minimal acute toxicity in many studies; long-term breakdown products require evaluation
Silica NPs (SiO_2 / MSNs)	Soil invertebrates, beneficial microbes	Soil exposure; mg kg^{-1}	Particle persistence; low acute toxicity in many assays but potential physical effects on organisms
Nano-clays (montmorillonite, kaolinite)	Soil fauna (worms), plants	Soil amendment levels; g kg^{-1} – mg kg^{-1}	Generally low chemical toxicity; may affect nutrient availability and soil pore structure
Green-synthesized NPs (plant-reduced Ag, etc.)	Aquatic invertebrates, algae	Water/sediment exposures; variable depending on synthesis	Antimicrobial and oxidative-stress related toxicity observed in some assays
Generic nano-herbicide formulations (encapsulated herbicides)	Non-target plants, soil microbes, earthworms	Field-application rates (a.i. concentrations reflect reduced doses vs. conventional)	Often lower off-target toxicity due to targeted delivery, but depends on carrier degradation and breakdown products
Metal-oxide mixtures / multi-component NPs	Multi-trophic aquatic organisms (algae → daphnia → fish)	Mixed exposures; environmentally realistic concentrations not well established	Synergistic toxicity in some studies; oxidative stress and impaired growth reported

Source: Wang et al., 2022; Karadbhajne et al., 2024; Jampílek & Kráľová, 2015

5. REGULATORY GAPS AND RISK ASSESSMENT

Despite growing interest in nano-herbicides, regulatory frameworks have not kept pace with their rapid development. Current pesticide registration protocols often do not account for the novel behaviors and risk profiles of nanomaterials (Côa et al., 2020). This gap poses challenges for establishing safe use thresholds, monitoring environmental residues, and ensuring long-term ecological protection.

Harmonized and nanoparticle-specific risk assessment methodologies are urgently needed (Eghbalinejad et al., 2024). These should incorporate chronic exposure studies, life-cycle analyses, and ecosystem-level evaluations (Chidiamassamba et al., 2024). Additionally, the use of biodegradable carriers such as chitosan offers a potential mitigation strategy by reducing persistence and toxicity (Jayasoorya & Kumar, 2024), but further field-based research is required to confirm their environmental safety under variable conditions.

5.1 Future Prospects and Research Directions

The advancement of nano-herbicides offers a range of opportunities to improve agricultural productivity, environmental sustainability, and weed management precision (Rani et al., 2024; Zain et al., 2023). Future research directions include developing biodegradable nanocarriers, integrating nanotechnology with precision agriculture, applying genome-targeted delivery, and creating multifunctional nanomaterials that combine weed control with nutrient delivery.

5.1.1 Development of biodegradable nano-carriers

Biodegradable nanocarriers are central to improving the environmental safety of nano-herbicides. Current research focuses on polymeric and biopolymeric nanoparticles that maintain herbicide stability while breaking down into non-toxic byproducts (Demirel et al., 2021). However, challenges remain, including biocompatibility, toxicity, and the ability to cross plant and soil biological barriers effectively (Daglar et al., 2014). Stimuli-responsive systems activated by pH, temperature, or enzymes could enhance targeted delivery while reducing off-target effects (Xiao et al., 2024; Parvin et al., 2025). Moreover, green nanotechnology approaches, such as using agricultural bio-wastes or plant-derived polymers, offer potential for sustainable, low-toxicity carriers (Petrovic & Barbinta-Patrascu, 2023).

5.1.2 Integration with precision agriculture

The fusion of nanotechnology with precision agriculture can optimize resource efficiency and minimize environmental impacts. Nano-fertilizers, with controlled nutrient release, improve plant uptake and reduce leaching losses (Alam et al., 2024; Sharma et al., 2024). Nanosensors can monitor soil nutrient levels, plant stress, and pest presence in real time, enabling site-specific herbicide and fertilizer applications (Singh, 2023). Nano-enabled biocontrol agents and nanopesticides also allow targeted application, lowering chemical inputs and reducing non-target effects (Sirajo et al., 2024). However, widespread adoption is limited by potential toxicity, high production costs, and incomplete regulatory frameworks (Lallawmkimi et al., 2025).

5.1.3 Genome-Targeted Nano-Herbicide Delivery

Genome-targeted nano-herbicides could revolutionize weed control by selectively silencing or editing essential genes in invasive weeds (Paul et al., 2024). While this specificity reduces chemical load and off-target damage, it may also exert strong selective pressure, accelerating the evolution of resistant weed biotypes and narrowing plant genetic diversity (Verma & Saroop, 2024). Additionally, nanoparticle carriers used in genome delivery can disrupt soil microbial communities (Gupta et al., 2024) and potentially bioaccumulate in food webs. Regulatory oversight and biodiversity protection strategies will be necessary to ensure that genetic control approaches do not destabilize ecosystems (Ullah et al., 2024).

5.1.4 Multi-functional nanomaterials (herbicide + fertilizer)

Designing multifunctional nanomaterials that combine herbicide and fertilizer delivery could improve nutrient use efficiency while controlling weeds. Nanoencapsulation allows both agents to be co-delivered in a controlled manner, with smart release triggered by soil moisture, pH, or root exudates (Bratovcic et al., 2021; Kaushik & Djiwanti, 2017; Shah et al., 2019). Synergistic formulations can reduce application frequency, enhance crop resilience, and lower overall chemical usage (Yin et al., 2023; Rasool et al., 2024). This approach also has the potential to reduce nutrient runoff, contributing to environmental protection (Bhushan et al., 2024). However, long-term environmental monitoring will be essential to assess accumulation risks and unintended ecological effects.

6 CONCLUSION

The emergence of nano-based herbicides offers a transformative opportunity for addressing the persistent and evolving challenge of invasive weed management in agriculture. By leveraging nanoscale delivery systems, these formulations enhance herbicide efficiency, reduce application dosages, improve target specificity, and minimize environmental leakage compared to conventional products. Evidence from recent studies demonstrates their capacity to control resistant weed populations, extend herbicide activity through controlled release, and maintain crop safety at lower chemical loads.

However, despite these promising outcomes, several critical challenges remain before nano-herbicides can be widely adopted. Knowledge gaps persist regarding their long-term environmental fate, potential toxicity to non-target organisms, and interactions with soil and aquatic ecosystems. Moreover, the absence of nanoparticle-specific regulatory frameworks poses a barrier to commercialization and safe deployment. Addressing these uncertainties will require multidisciplinary research, harmonized risk assessment protocols, and field-based evaluations under diverse agroecological conditions.

In moving forward, the integration of nano-herbicides with precision agriculture, biodegradable carrier systems, and potentially genome-targeted delivery approaches holds significant promise. Such innovations, coupled with responsible governance and stakeholder engagement, could enable nano-herbicides to become a cornerstone of sustainable, resilient, and ecologically balanced weed management strategies. Ultimately, their successful adoption will depend not only on technological advancements but also on a comprehensive understanding of their environmental implications, economic viability, and role within integrated weed management systems.

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Ethics

This manuscript presents an original review that has not been submitted anywhere for consideration. The corresponding author confirms that all co-authors have reviewed and approved the submission, and no ethical concerns are associated with its publication.

Conflict of Interest

No conflict of interest exists.

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