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Application of Nanotechnology for Integrated and Precision Weed Management in Agriculture: Nano-herbicides, Nanocarrier-Mediated Delivery, Herbicidal Efficiency, Resistance Management, and Environmental Considerations – A Review

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***Abstract*—** *The science of manipulating materials at the nano-scale is known as nanotechnology. Nanotechnology is a key component of the most recent advancements in technology. Precision farming will come from the use of minimal pesticides and herbicides as well as increased efficiency, controlled release, and application to a specific target. Crop improvement is a constant process in agriculture. The management of perennial weeds and the degradation of the weed seed bank are issues that are being tackled through the development of nano-herbicides. This technology also emphasizes the development of nano-herbicides to deal with weed control and details of potential applications and strategies for weed management using nanotechnology.*

Keywords*— *Nanotechnology, nano-herbicides, nanoparticles, Weed management, Agriculture.

I. INTRODUCTION

Changes in agricultural technology have been a major factor shaping modern agriculture. Among the latest line of technological innovations, nanotechnology occupies a prominent position in transforming agriculture and food production. The development of nano-devices and nano-materials could open up novel applications in plant biotechnology and agriculture (Scrinis & Lyons, 2007). Nanotechnology permits broad advances in agricultural research, such as reproductive science and technology, conversion of agricultural and food wastes to energy and other useful by-products through enzymatic nano-bioprocessing, disease prevention and treatment in plants using various nano-cides (Moraru et al., 2003). Nanotechnology is the science of working with the smallest particles, increases hope to improve the productivity of agricultural ecosystems, through encounter with problems that have remained unanswered by customary practices and has opened a new way in farming.

The use of chemical herbicides is a common method to control weeds, which in addition to the beneficial effects on weed control can have harmful effects such as environmental pollution, residue in soil and damage to next crop, resistance in weeds and they also have difficult control. In recent years, scientists using nanotechnology and production of nano-herbicide attempted to solve this problem. Nano-herbicides with features such as effective concentration, time-controlled release in response to specific stimuli, increased activity at the target site and less toxicity for ecosystem can be a good alternative to chemicals, and prevent the occurrence of problems and challenges arising from the use of herbicides in weed management.

The powerful technology of nanotechnology allows us to study atomic and molecular level structures at the nano-level. Research and development in nanotechnology is predicted to increase the agricultural sector's use of genetically modified crops, precision farming, chemical pesticides, and inputs for animal production (Abd-Elrahman & Mostafa, 2015). Nanotechnology is an interdisciplinary field with applications in chemistry, physics, biology, medicine, and engineering, among other applied sciences. The study of materials with atomic, molecular, and supramolecular dimensions in order to understand, control, and measure them is known as nanotechnology. Or, to put it another way, nanotechnology is the manipulation or self-assembly of individual atoms, molecules, or molecular clusters into structures to produce materials and technologies with brand-new or vastly different characteristics. For example, photonics applications in nano-electronics and nano-engineering, which require shrinking the size of the smallest structures to the nano-scale, are examples of how nanotechnology can operate from the top down or the bottom up (which involves manipulating individual atoms and molecules into nanostructures and more closely resembles chemistry or biology).

One billionth of a metre is known as a nanometre. Generally speaking, the term "nano" refers to a scale of size between 1 nanometre (nm) and 100 nm in at least one dimension, and relates to the development or modification of materials or electronics within that range. Technically speaking, "nano" refers to 10^{-9}, or one billionth of something. For comparison, the wavelength of visible light is between 400 nm and 700 nm. A leukocyte has the size of 10,000 nm, a bacteria 1000-10,000 nm, virus 75-100 nm, protein 5-50 nm, glucose 1 nm, deoxyribonucleic acid (DNA) ~2 nm (width), and an atom ~0.1 nm. In this scale, physical, biological and chemical characteristics of materials are fundamentally different from each other and often unexpected actions are seen from them. Nanotechnology considers the topics with viruses and other pathogens scale, so it has high potential to identify and eliminate pathogens (Prasanna, 2007 & Predicala, 2009).

Recent advances in nanotechnology have made it possible to create nano-scale structures that can be controlled, regulated, and used to accelerate chemical reactions. Nanomaterials are made up of very smaller components, and the properties of materials at the macro level are affected by these parts. Nanoparticles can act as "magic bullets," releasing herbicides, drugs, or genes that are targeted at specific plant tissues. Herbicides can be effectively absorbed by nano-capsules through tissues and cuticles, allowing for a steady release of the active ingredients. Nanobiotechnology refers to the nano-scale fusion of technology and biology (Perea-de-Luque & Rubiales, 2009). The current era's sixth revolutionary technology is emerging as nanotechnology. It is believed to be an emerging branch of science that is extensively embraced in many scientific domains and is anticipated to play a major role in the fields of agriculture and food science in the future; however, there are currently few scientific studies about its use in agriculture globally (Mousavi & Rezaei, 2011).

The use of materials and equipment that can utilize a substance's physical and chemical characteristics at the molecular level to explore the biological and material worlds in nano-scale size is known as nanotechnology. It can be applied in a variety of fields, such as medicine and agriculture (Fakruddin et al., 2012). Nanotechnology is the study and application of small things, specifically of materials with a size of less than 100 nm. Nanotechnology integrates solid state physics, chemistry, chemical engineering, biochemistry, biophysics, and materials science; one nanometre is equal to 10^{-9} metres.

According to recent studies, nanotechnology has the potential to enhance farming techniques by improving the effectiveness of farm inputs and offering solutions to agricultural and natural resource concerns. Based on current ecological conditions, agricultural disease detection and control, and improving crops' ability to absorb minerals from the soil, nanotechnology will increase crop productivity (Alfadul et al., 2017). Nanotechnology will substitute all agricultural endeavours (Mukhopadhyay, 2014).

The characteristics of nanoparticles comprise extremely small size (1-100 nm), high activity, and chemical and optical attributes unique to this size range (Khan & Rizvi, 2014). Hydrophilicity, miscibility, unevenness, structure, adsorption during synthesis, ability to produce superoxide radicals, stoichiometry, competitive receptor binding ability, dispersion, and agglomeration are some of the attributes of nanoparticles (Somasundaran et al., 2010). Nanoparticles are useful in a wide range of disciplines and have brought up a lot of opportunities for scientific research in agriculture (Kanjana, 2015). Nano-aluminum has been widely used in various industries and hence there is greater chance for the interaction of such nanomaterials with higher plants that constitute a major portion of the ecosystem. Pure alumina nanoparticles (13 nm) without any modifications reduced root elongation in studied plants (corn (*Zea mays*), cucumber (*Cucumis sativus*), soybean (*Glycine max*), carrot (*Daucus carota*) and cabbage (*Brassica oleracea*) thus potentially retarding the growth of plants (Yang & Watts, 2005). Seed germination of rye grass and corn was inhibited by nanoscale zinc (nano-Zn (35 nm)) and zinc oxide (nano-ZnO (15–25 nm)) respectively (Lin & Xing, 2007).

II. REVIEW METHODOLOGY

This narrative review was prepared to: (i) explain the fundamentals of nanotechnology relevant to weed management; (ii) identify the challenges of conventional herbicide use; (iii) summarize the development and application of nano-herbicides; (iv) discuss smart delivery mechanisms and detoxification of herbicide residues; and (v) evaluate environmental and safety aspects of nano-herbicides.

Literature was identified through targeted searches of journal databases including Web of Science, Scopus, PubMed Central, and Google Scholar using search terms including "nanotechnology," "nano-herbicides," "weed management," "nanoparticles," "smart delivery systems," "herbicide resistance," and "environmental safety." Foundational papers necessary to define the field were included alongside more recent studies. Species or application examples are reported as documented examples only when supported by the cited source.

III. NANOTECHNOLOGY FUNDAMENTALS AND AGRICULTURAL APPLICATIONS

3.1 Definition and Scope

Nanotechnology is the science of manipulating materials at the nano-scale (1-100 nm). It is a key component of the most recent advancements in technology and is an interdisciplinary field with applications in chemistry, physics, biology, medicine, and engineering. The study of materials with atomic, molecular, and supramolecular dimensions in order to understand, control, and measure them is known as nanotechnology. It can be applied in a variety of fields, such as medicine and agriculture (Fakruddin et al., 2012).

3.2 Nanoparticle Characteristics

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3.3 Nanotechnology in Agriculture

According to recent studies, nanotechnology has the potential to enhance farming techniques by improving the effectiveness of farm inputs and offering solutions to agricultural and natural resource concerns. Based on current ecological conditions, agricultural disease detection and control, and improving crops' ability to absorb minerals from the soil, nanotechnology will increase crop productivity (Alfadul et al., 2017). Nanotechnology will substitute all agricultural endeavours (Mukhopadhyay, 2014). The development of nano-devices and nanomaterials could open up novel applications in plant biotechnology and agriculture (Scrinis & Lyons, 2007). Nanotechnology permits broad advances in agricultural research, such as reproductive science and technology, conversion of agricultural and food wastes to energy and other useful by-products through enzymatic nano-bioprocessing, disease prevention and treatment in plants using various nano-cides (Moraru et al., 2003).

IV. NANOTECHNOLOGY AND WEED MANAGEMENT

4.1 Challenges in Conventional Weed Management

Weeds may threaten the complete harvest in sensitive agro-ecosystems because 2/3 of Indian agriculture is rainfed cultivation, which uses relatively little herbicide. Market-available herbicides are made to kill or control the weed plants' above-ground growth. None of the herbicides prevent the growth of rhizomes or tubers, which are active belowground plant portions that serve as a seed for new weeds the following season. Lower yields than soils where weeds are controlled are likely to result from weed infestations and weed seeds (Chinnamuthu & Kokiladevi, 2007).

The most significant pests in terms of economic impact and environmental harm are weeds, and most insecticides used globally are directed at them. For instance, insecticides account for 29% of global agrochemical sales, while herbicides account for 47% (McFadyen, 1998). Herbicide resistance and poor control were the consequences of a multi-species approach with a single herbicide in a cropped environment. When a plant community is repeatedly exposed to one herbicide in one season and another herbicide in another season, resistance eventually develops and the plant community can no longer be controlled by chemicals (Chinnamuthu & Kokiladevi, 2007).

4.2 Nano-Herbicides for Effective Weed Control

In agriculture, weeds are a major threat since they significantly lower the yield. Therefore, the only choice is to completely eradicate them. Without leaving any hazardous residues in the soil or environment, nanotechnology has the ability to eradicate weeds through the use of nano-herbicides in an environmentally friendly manner (Pérez-de-Luque & Rubiales, 2009). Improvements in the efficacy of herbicides through the use of nanotechnology could result in greater production of crops. There are now inert ingredients for herbicide application that say they contain nanomaterials. When glyphosate is treated with a "nanotechnology-derived surfactant," it has been observed that glyphosate-resistant crops become sensitive to the herbicide. Crops that are resistant to glyphosate are potentially susceptible to it thanks to a soybean-based nanosurfactant (Chinnamuthu & Kokiladevi, 2007).

Nano-encapsulated agrochemicals should be designed in such a way that they possess all necessary properties such as effective concentration (with high solubility, stability and effectiveness), time controlled release in response to certain stimuli, enhanced targeted activity and less ecotoxicity with safe and easy mode of delivery thus avoiding repeated application (Green & Beestman, 2007; Wang et al., 2007; Boehm et al., 2003; Tsuji, 2001). The control of parasitic weeds with nano-capsulated herbicides thereby reducing the phytotoxicity of herbicides on crops is a best example (Pérez-de-Luque & Rubiales, 2009). Properly functionalized nano-capsules provide better penetration through cuticle and allow slow and controlled release of active ingredients on reaching the target weed. Nano-encapsulation of chemicals with biodegradable materials also makes the concentrated active ingredients safe and easy to handle by the growers.

Nano-herbicides are different forms of herbicides developed in collaboration with nanomaterials, and they are herbicides encapsulated in synthetic polymer core shell nanoparticles (Kumar et al., 2015). To eliminate individual weeds by acting on specified root receptors, nanoparticles incorporating target-specific herbicides are used (Jampílek & Kráľová, 2015). The design of a target-specific herbicide chemical encapsulated in a nanoparticle is directed at a specific binder of target weed roots that encompasses the root system and is translocated to the areas that obstruct roots' glycolysis. The outcome is that the weed plant will starve to death (Chinnamuthu & Kokiladevi, 2007).

4.3 Smart Delivery Mechanisms

"Smart Delivery Systems" in agriculture should possess combinations of time controlled, specifically targeted, highly controlled, remotely regulated/pre-programmed/self-regulated and multifunctional characteristics to avoid biological barriers for successful targeting. Agriculture and food system security, novel delivery systems for disease treatment, new tools for molecular and cellular biology and new materials for plant pathogen detection are some of the nano-technological links to agriculture and food science. Besides these, plants and/or their extracts provide a biological synthesis route of several metallic nanoparticles which is more eco-friendly and allows a controlled synthesis with well-defined size and shape (Kumar & Yadav, 2009; Sharma et al., 2009).

The introduction of a target-specific herbicide compound enclosed in a nanoparticle is directed to a specific receptor in the roots of the target weeds, where it enters the system and travels to regions that hinder the hydrolysis of food reserves in the root system. This will cause the particular weed plant to run out of nourishment and die (Chinnamuthu & Kokiladevi, 2007). Herbicide treatment with insufficient soil moisture may result in loss as vapour in rain-fed locations. Still, it is difficult for us to accurately forecast when it will rain; pesticides cannot be used in advance to prepare for it. The competing weeds with crops should be eliminated via the controlled release of encapsulated pesticides.

Herbicide usage can be prevented by using nanotechnology, which also provides safe and effective delivery methods (González et al., 2014). When nanoparticles are sprayed to leaf surfaces, they move to different tissues after entering through stomatal holes or the bases of trichomes (Uzu et al., 2010; Fernández & Eichert, 2009; Eichert et al., 2008). The valuable feature of utilizing magnetic nanoparticles is that they enable highly precise localisation of the particles to release their load, which is of considerable interest in the research of nano-particulate delivery for plants. A few experiments on the uptake, translocation, and precise localisation of magnetic nanoparticles (less than 50 nm) in pumpkin plants have been published (González-Melendi et al., 2008; Zhu et al., 2008; Corredor et al., 2009).

4.4 Carbon Nanotubes and Weed Seed Germination

Carbon nanotubes also breach the dormancy of weed seeds, speed up germination, and cut germination time in half by forming tubes that cause breaches in the seed coat that allow water and chemicals to enter (Khodakovskaya et al., 2009). Molecular characterisation of underground plant parts for a novel target domain (Zimdahl, 2018) may lead to receptor-based herbicide molecules with specific binding properties using nano-herbicide molecules like carbon nanotubes capable of killing the viable and dormant underground propagules of weed seeds.

V. DETOXIFICATION OF HERBICIDE RESIDUES

Herbicides that are used in excess leave residue in the soil and harm succeeding crops. Herbicide-resistant weed species evolve as a consequence of repeated exposure and the weed flora changes. Atrazine, an s-triazine ring herbicide, is used globally for the control of pre and post-emergence of broadleaf and grassy weeds. Herbicide use is at risk of becoming frequently used due to residual issues caused by the use of atrazine, which also restricts the types of crops that can be rotated.

Recent research from Tamil Nadu Agricultural University gives hope that atrazine residue in soil can be removed quickly. Under controlled conditions, application of silver modified with magnetite nanoparticles stabilised with Carboxy Methyl Cellulose (CMC) nanoparticles resulted in 88% breakdown of herbicide atrazine residue (Susha et al., 2008). Atrazine is a commercially used herbicide with a long half-life (125 days) and increased mobility in some soils for the control of weeds with broad leaves and grassy characteristics that emerge before and after planting. Atrazine residues were broken down by 88 percent when silver was combined with magnetite nanoparticles and stabilised with Carboxy Methyl Cellulose (CMC) nanomaterial under controlled conditions (Susha et al., 2008).

VI. MECHANISMS OF HERBICIDE ACTION AND NANOTECHNOLOGY

Herbicides administered topically to perennial weeds like *Cynodon dactylon*, *Cyperus* spp., and *Solanum elaeagnifolium* do not totally eradicate them. Inhibiting lipid biosynthesis, interfering with cell division by disrupting the mitotic sequence or preventing the mitotic entry, destroying the structure and function of the plant-specific chloroplast, destroying cellulose biosynthesis, and deregulating auxin-induced cell growth are among the target areas of today's herbicides in a plant cell (Boger & Sandmann, 1989; Wakabayashi, 1989; Wakabayashi, 1993; Wakabayashi & Sato, 1992; Wakabayashi & Böger, 2004).

Root absorption is less complicated than foliar absorption. Although mature roots are coated by a suberized layer, mature roots do not have cuticles like leaves do. This indicates that plant roots have few obstacles to absorbing herbicides. Herbicides that are lipophilic will be easily absorbed because roots are fundamentally lipophilic. About 60% of conventional herbicides interfere with the photo-electron transport system of the chloroplast, despite the fact that molecular mechanisms of action for even some commercially available herbicides are still not fully understood. There are currently no commercial herbicides that prevent the formation of sugar and the fixation of CO_2. Creating a receptor-based herbicide molecule with particular binding properties using nano-herbicide molecules like carbon nanotubes capable of killing the viable and dormant underground propagules of weed seeds offers a promising approach (Zimdahl, 2018).

VII. ENVIRONMENTAL AND SAFETY ASPECTS OF NANO-HERBICIDES

7.1 Benefits of Nano-Herbicides

The integration of nanotechnology in agriculture, particularly through nano-herbicides, offers significant promise in enhancing efficacy and environmental safety in weed management (Susha et al., 2022). Nano-enabled agricultural technologies address the growing need for increased crop yields while reducing environmental impact (Yin et al., 2018). Nano-herbicides represent one application in this field, where nanoscale formulations deliver active ingredients with higher precision and controlled release, resulting in improved bioavailability and reduced chemical usage (Zargar et al., 2023). These properties allow for efficient weed control at lower doses and with less frequent applications, leading to more sustainable agricultural practices (Bajwa, 2014).

A distinct advantage of nano-herbicides lies in their increased surface area, which enhances interactions with target weed species and allows for more efficient absorption and bioavailability of active components (Paul et al., 2024). These properties enable deeper penetration of active ingredients into pest tissues, prevent premature degradation, and reduce losses to the environment, thus extending their effectiveness (Shang et al., 2019). By minimizing environmental runoff and reducing the total volume of chemicals needed, nano-herbicides help limit off-target effects, protecting non-target plants, soil, and water ecosystems while contributing to increased crop productivity. Additionally, nanomaterials as carriers can achieve site-specific targeting of herbicides, allowing controlled delivery to specific areas where they are most needed (Narware et al., 2019).

In addition to direct weed control, nanotechnology advancements have facilitated the development of nanobiosensors for environmental monitoring and detection of plant stressors, including weed infestations. These technologies support precision agriculture by enabling real-time monitoring, which optimizes weed management through timely, targeted applications (Shang et al., 2019). Such smart technology aids in reducing the overall chemical load by ensuring that herbicides are applied only where and when necessary, further enhancing environmental sustainability.

7.2 Risks and Side Effects of Nano-Herbicides

However, despite the benefits, the environmental and safety implications of nano-herbicides require careful consideration. Although these formulations reduce the overall chemical input, nanoparticles may persist in soil and water, raising concerns about their long-term ecological impact (Narware et al., 2019). Persistent nanoparticles could potentially disrupt soil microflora and aquatic ecosystems, which necessitates the development of biodegradable nanoparticles that can naturally decompose, such as those based on chitosan (Chugh et al., 2021). Regulatory frameworks and ongoing environmental risk assessments are critical to ensuring that nano-enabled weed management solutions remain effective while safeguarding ecological integrity, thus supporting a balanced approach to sustainable agriculture.

The potential for nanoparticles to bioaccumulate in food products and penetrate intact human skin are just two of the many threats that come with the misuse of nanotechnology. The health of humans and animals is especially at risk from airborne nanoparticles. Unintended effects on non-target plants and related creatures are another source of worry. Nano-herbicides, for instance, have the potential to disrupt pollination by blocking plant vascular bundles. Potential problems include phytotoxicity, cytotoxicity, and genotoxicity, which may result in DNA alterations or cellular damage. Additionally, certain algal and soil microbial populations may be negatively impacted by nanomaterials (Sakarvadia, 2022; Alama et al., 2023; Pradhan et al., 2024; Chikowo et al., 2009).

7.3 Regulatory and Risk Assessment Considerations

Safety evaluation should include nanoparticle characterization, screening for toxicity, environmental persistence, non-target effects, and bioaccumulation potential. Regulatory systems may differ for a single nanoparticle formulation, a mixed formulation, or a nano-enabled delivery system. Claims should distinguish a research formulation from a registered commercial product. A traceable chain of identity, formulation, quality control, and field performance is required for responsible translation.

VIII. CONCLUSIONS AND FUTURE OUTLOOK

Nanotechnology is transforming agriculture, especially in sustainable weed management with the use of nano-herbicides. These nanoscale formulations improve the effectiveness of herbicides, decrease the amount of chemicals used, and lessen off-target effects, thereby supporting sustainable farming practices. However, for widespread adoption, comprehensive environmental and health risk assessments are necessary.

Current research is fostering innovation in advanced delivery systems that allow for precise herbicide application, which helps to minimize environmental exposure. The integration of smart nano-sensors for real-time monitoring of plant health, soil quality, and weed detection is enhancing precision agriculture. Biodegradable nanomaterials provide eco-friendly alternatives, and their combined use with biological control methods and integrated pest management is bolstering weed management strategies. Creating a regulatory framework is crucial for the responsible use of nanotechnology, ensuring a sustainable, resilient, and productive future for agriculture.

Limitations of this Review: This review is based on a narrative synthesis of published literature rather than a formal systematic review. The examples are selected to illustrate the diversity of approaches and should not be considered exhaustive. The focus is primarily on nano-herbicides and delivery systems, with less attention to other nanotechnology applications in weed management such as nanosensors and nanobiosensors.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript

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