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OPINION

The possible role of nanotechnological interventions in weed management – An opinion

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ABSTRACT

Nanotechnology is rapidly becoming one of the most essential tool in modern agriculture and it has the potentiality to play major role in managing weeds too in agroecosystems as the emerging weed problems can not be solved by adoption of conventional methods alone. Nanoparticles can be synthesized in many ways using top-down approach or bottom-up approach. Among these, the green synthesis of nanoparticles using plant or microorganisms is the eco-friendly and safest method of nanoparticle synthesis. Nanoparticles have wide range of applications in managing weeds and overcoming perennial weed menace through exhausting weed seed bank, breaking weed seed dormancy by degrading germination inhibitors, inhibiting viable underground plant parts by exhausting food reserves, improving foliar absorption and translocation *etc*. They can also be used in smart delivery mechanism of herbicides for rainfed ecosystems and as slow-release nano formulations for season long weed control. Nano formulations currently used in weed management are nano-encapsulation, nano-carrier, nano emulsion, nano-adjuvants, nano-biosensors *etc*. Nanotechnology reduces the application rate of herbicides per hectare and minimise environmental pollution and CO_2 emission. Nano formulations are effective against herbicide resistant weeds and enhances the rate of mitigation of herbicide residues in soils. The nanotechnology holds promise for attaining sustainable agriculture through their effective and judicious use in development and adoption of weed management technologies, particularly in under developed nations.

Keywords: Nanotechnology, Detoxification, Nanoencapsulation, Smart delivery, Weed management

Yield losses due to weeds are a major threat to crop production and farmers' economic well-being. In India, total actual economic loss of about USD 11 billion was estimated due to weeds in 10 major crops alone of which rice accounts for loss of USD 4420 million, wheat for USD 3376 million and USD 1559 million for soybean (Gharde *et al*. 2018). Weeds also impair product quality and cause health and environmental hazards. Herbicides are one of the effective management tools to control weeds either alone or in integration with physical, cultural, and biological methods. Herbicides account for 47.5% of the overall yearly pesticide use of 2 million tonnes. But the over-reliance on herbicides has adverse impact on environment, non-targeted organisms, pollution of soil and water bodies, and the emergence of herbicide-resistant weeds (Choudhary 2020). Weeds have acquired resistance to 164 different herbicides, as well as 21 of the 31 known herbicidal mode of action. Herbicide-resistant weeds have been discovered in 95 crops across 71 nations (Heap 2021). There are 509 distinct cases of weed resistance to herbicides in the globe, including 266 different species (153 dicots and 113 monocots).

In spite of significant developments in weed management research in India (Rao *et al*. 2020), several challenges still prevail including: the non or lesser impact of existing physical and cultural methods on underground plant parts of perennial weeds like *Cyperus rotundus*; labour intensiveness of currently used mechanical methods, restriction of herbicides effect to temporary inhibition of weed seed production due to marginal transfer of herbicides sprayed; the dependence of herbicide efficacy on factors like soil type, soil moisture, humidity and air temperature at the time of application; lack of selective herbicides for perennial weeds; increasing weed seed bank size due to management of currently used practices on emerged weeds only; the development of weeds herbicide resistance and issues related to herbicide residues. Thus, tackling of these challenges necessitates research and adoption of innovative technologies usage of which nano-technology is prominent.

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Nanotechnology

Nanotechnology is the science of altering nanoscale materials and has a wide range of uses in the agricultural industry. It uses a variety of chemical agents and new delivery mechanisms to boost agricultural output while also reducing the usage of bulk agrochemicals. Nanotechnology can provide better answers to existing agricultural challenges by reducing the use of herbicides and insecticides while increasing their efficiency.

Nanotechnology is a combination of applicable sciences such as chemistry, physics, biology, medicine, and engineering in which matter structure is controlled at the nanometre scale to develop materials with unique properties such as huge surface area, target site of action, and progressive release. It refers to materials, systems, and processes with a scale of less than 100 nanometers (nm). The size of nano-particles range from 1 - 100 nm in one dimension. The name "Nano" comes from the Greek word "nanos," which means "dwarf" (small). Nobel laureate Richard Feynman initially introduced nanotechnology in 1960 with his famous lecture "There's plenty of room at the bottom". Nanotechnology is mainly concerned with the separation, consolidation, and deformation of materials by a single atom, molecule, or ions. Nanoparticles have important characteristics such as morphology-aspect ratio or size, hydrophobicity, solubility-release of active ingredients, high surface area or roughness, surface species contaminations or adsorption during synthesis, reactive oxygen species (ROS), capacity to produce ROS, structure, composition, competitive binding sites with receptor, dispersion and aggregation (Somasundaran *et al.* 2010). Carbon-based nano particles (NPs), quantum dots and nanorods, metallic NPs, ceramics NPs, semiconductor NPs, polymeric NPs, lipid-based NPs, micro and nano encapsulation, and nano emulsion are all examples of nanomaterials now in use.

The nanotechnology has a number of advantages due to the unique functional qualities of nanoparticles and materials. The advantages include: the greater charge density and reactivity provided by the smaller size of the nano-particles; the enhanced activity of the atoms on their surfaces which exceeds that of the atoms inside the particles as the surface area of the particles increase with respect to their volume; nano particles' greater strength, increased heat resistance, decreased melting point, and variable magnetic properties as a result of the high surface-to-volume ratio; variations in atomic distribution across nanoparticles due to differences in exposed surfaces, which impact the rate of electron transfer kinetics between metal nanoparticles and corresponding adsorbed species; higher catalytic activity of tetrahedral nanoparticles, than cubic and spherical nanoparticles, which are recognised for improving chemical reactivity at sharp edges and corner. As per published European Commission (EC) recommendation, a nanomaterial is defined as "natural, incidental, or industrial material with particles, in an unbound state or in the form of aggregate or agglomerate where 50% or more of the particles in the number and size distribution, one or more than one dimensions lies in the range of 1–100 nm" (Neme *et al.* 2021).

The nanoparticle synthesis

A variety of methods are being used for the synthesis of nanoparticles, which are generally categorised into two categories (Royal Society and Royal Academy of Engineering).

(a) Top-down approach (which focus on reducing the size of bulk materials) and

(b) Bottom-up approach (where materials are synthesised from the atomic level)

Top-down: In top-down approach, mechanical-physical procedures such as grinding, milling, and crushing are used to manipulate a small number of atoms or molecules to construct exquisite patterns. This approach makes substantial use of nano composites and nano-grained bulk materials such as metallic and ceramic nanomaterials (10 - 1000 nm).

b) Bottom-up: In a 'Bottom-up' approach, several molecules self-assemble in parallel steps based on their molecular recognition characteristics. From atoms or molecules, this processing yields increasingly complex structures. This approach is mostly used to produce nanomaterials with consistent sizes, morphologies, and size ranges (1 - 100 nm).

Several microorganisms and higher plants were found to be effective, ecologically friendly nano-

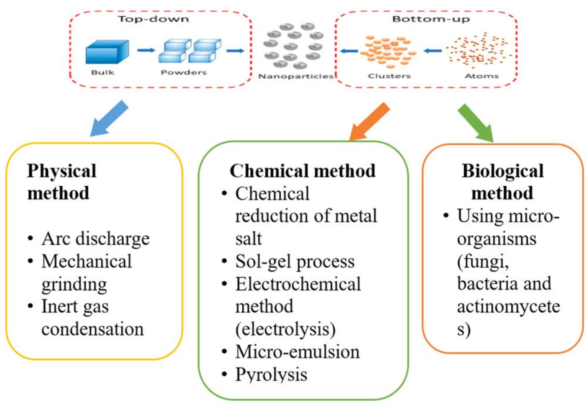

Figure 1. Synthesis of nanoparticles (Patra and Baek 2014)

factories for the production of nanoparticles, based on organism's natural systems for removing heavy metals and radionuclides from their environment (Singh *et al.* 2019). They include: a) plant-mediated biosynthesis and b) micro-organisms mediated and involving biosynthesis.

NANO TECHNOLOGY-BASED INTERVENTIONS IN WEED MANAGEMENT

Weed seed bank and perennial weeds perennating organs exhaustion

One of the most widely used applications of nano-herbicides is in the exhaustion of the weed seed bank. Instead of destroying the seedling, carbon nanotubes (CNTs) kill the weed seeds. These nano tubes induce cracks and openings in the seed coat, allowing water and chemicals to pass through. This breaks the seed's dormancy, speeds up germination and cuts the germination time in half.

Nanoherbicides are also used to overcome the perennial weed menace by killing viable underground plant organs of perennial weeds such as rhizomes and tubers, which help in faster propagation of those weeds. The use of H_2O_2 at 300 ml/m^2 followed by pendimethalin at 0.75 kg/ha + ZnO nanoparticles at 500 ppm/m^2 resulted in a significant reduction in weed emergence patterns due to the disruption in the seeds before and during their emergence, and resulted in increase in blackgram yield (Vimalrajiv *et al.* 2018).

Germination promotion by germination inhibitor degradation

In *Cyperus rotundus* (purple nutsedge) tubers, phenols are the major factor of dormancy because of which *C. rotundus* tubers persist and interfere with the growth of crops during the following season. Maximum degradation of the phenolic compound vanillic acid was reported with iron oxide (Fe_2O_3) nanoparticles at 25 mg *i.e.*, 60.6% degradation relative to control (Viji and Chinnamuthu 2019). The enhanced degradation of phenols and dormancy breakdown the enhanced germination of *C. rotundus* tubers was observed with the treatment of zinc oxide nanoparticle at 3 g/kg (Viji and Chinnamuthu 2015b) and iron oxide (Fe_2O_3) nanoparticles at 25 mg (Viji and Chinnamuthu 2019). Iron oxide nanoparticles resulted in a higher percentage of phenol breakdown (89%) than the control at 3.0 g/kg tubers (Viji and Chinnamuthu 2015a). According to Brindha and Chinnamuthu (2017) ZnO nanoparticles significantly decompose phenolic compounds in *C. rotundus*. Tubers of *C. rotundus* treated with ZnO nanoparticles at dosages of 1500 mg/kg in dry form (powder form) and 2250 mg/kg in wet form (liquid form) had a substantial impact on tuber germination via degradation of phenol and biochemical components.

Perennial weeds management through exhaustion of food reserves

The nano-particles encapsulated with herbicide molecules are used to target the receptors present in the roots of the weed. After their entry, their translocation in the system causes inhibition of glycolysis which deprives the plants of food reserves leading to starvation and death. The food reserves in the tubers of *C. rotundus* are depleted by silver nanoparticles. The degradation of starch into reducing sugars is brought by the interaction of á amylase with silver nano-particles (Viji *et al.* 2016).

Faster foliar penetration, movement and impact in the plant system of nano-herbicides

Depending on the entry point, several tissues (epidermis, endodermis) and barriers (Casparian strip, cuticle) must be traversed by herbicides before reaching the vascular tissues (roots or leaves). Nanomaterials can move up and down the plant using the apoplastic and/or symplastic pathways, as well as radial movement to switch from one to the other. Endocytosis, pore formation mediated by carrier proteins, and plasmodesmata has all been postulated as methods for the internalisation of nanoparticles within cells (Perez-de-luque 2017).

According to Nguyen *et al.* (2014), negatively charged nanoparticles had a faster foliar penetration than those with a positive zeta potential. The presence of polysaccharides rich in galacturonic or glucuronic acid units gives plant cell walls a negative charge. Nanoparticles having a positive charge collect and aggregate on the tissue surface as a result of electrostatic contact. Negatively charged nanoparticles, on the other hand, have a larger distribution inside plants due to their poor interaction with the cell wall (Zhu *et al.* 2012).

Nanoparticles and nanomaterials will effectively enhance the foliar absorption of herbicides by: lowering the size of herbicide particles to nanoscale; dissolving the wax-impregnated lipid polymer with the nanoparticle in an active energy-demanding procedure; which enhances diffusion via wax, cutin, and pectin corridors when nanoparticle is mixed with herbicide as it becomes ionic; by reducing the interfacial surface tension of the droplet when nano adjuvants are added to a water droplet, leading the droplet to spread across the leaf surface; by provision of electrically charged electrons by nanoparticles.

A significant increase in herbicidal efficacy with herbicidal activity directly through the vascular tissue of the leaves after a foliar contact of a nano-formulation of atrazine with Indian mustard (*Brassica juncea* L.) and the ability to maintain herbicidal action at low doses was demonstrated (Bombo *et al.* 2019).

By transpiration pull, also known as acropetal translocation, nanocomposites increase concentration and travel with water and solutes. The addition of nanoparticles causes them to conjugate with glucose and spread throughout the plant system. The glyphosate translocation to the major tubers was greater when it was encapsulated with TiO_2 nanoparticles. The encapsulated glyphosate coupled with Fe_2O_3, Ag, and TiO_2 nanoparticles, secondary tuber formation of *C. rotundus* was inhibited during a 40-day observation period and the encapsulated glyphosate with various nanoparticles was found to be safe and had no significant effect on earthworm activity (Viji and Chinnamuthu 2015a).

Enhanced herbicide efficacy in rainfed ecosystem by smart delivery of nano formulations

In rainfed ecosystems, herbicide use under insufficient soil moisture may result in herbicide volatilization and lesser herbicide efficacy. In order to reduce the weed competition, controlled release of the nano-encapsulated herbicides is useful as nano encapsulated herbicides will have a dispersion effect on receiving adequate moisture in rainfed farming. On receiving rains, the weed seeds mortality occurs by the immediate release of new herbicide molecules. The release of Pend-CuCts (Pendimethalin-Copper Chitosan) nanoparticles in pH 5.5 (acidic) medium was highest, while the lowest release was recorded in pH 7.0 (neutral) medium (Itodo *et al.* 2017).

Layer-by-Layer method (LBL) was used to coat manganese carbonate core material with appropriate polymers such as sodium Poly Styrene Sulfonate (PSS) and Poly Allylamine Hydrochloride (PAH) to obtain water soluble core-shell particles to load herbicide active ingredient for controlled release in rainfed agriculture. The etching procedure was used to create hollow-shell particles from core-shell particles. To achieve controlled release of the herbicide active ingredient, these hollow-shell particles were loaded with pendimethalin using a passive method. Even at 230°C, the formulation remained intact and without any microbial degradation (Kanimozhi and Chinnamuthu 2012). The herbicide was successfully enclosed in a MnO_2 core shell shielded with bilayer polymers that would open up and release the active ingredient with the receipt of rainfall.

Slow-release nano formulations for season long weed control

Nanostructures have been developed as smart delivery systems to target specific sites and as nanocarriers for controlled herbicide release. Nanotechnology can improve existing crop management techniques in the short to medium term. Using systemic herbicides against parasitic weeds as nano capsules would help to avoid phytotoxicity on the crop. Nanoencapsulation can also improve herbicide application, providing better penetration through cuticles and tissues and allowing slow and constant release of the active substances (Pradeesh and Chinnamuthu 2020). The herbicides encapsulated inside the polymer were produced using a solvent evaporation approach to produce nanostructures by encapsulating with protecting material for slow release, antimicrobial component to reduce the microbial degradation and capping agents to sustain under unfavourable weather condition. (Kumar and Chinnamuthu 2014, 2017). It was observed to get slowly released based on the availability of moisture apart from being protected from adverse climatic factors. Their efficacy in managing weeds needs to be thoroughly studied at different locations across India.

Detoxification of herbicide residues

The long-term usage of herbicides leaves a large amount of residue in the soil, which might harm subsequent crops and the surface and groundwater sources have been known to be contaminated by herbicide residues. Hence, herbicide residue detoxification is important. Under regulated conditions, the use of silver modified with Fe_3O_4 nanoparticles stabilised with carboxy methyl cellulose (CMC) resulted in an 88 % degradation of atrazine (Susha *et al.* 2011). Paraquat and atrazine nano formulations were more effective against target weeds than pure herbicides, whereas genotoxicity and cytotoxicity tests demonstrated that non-target plants such as onion (*Allium cepa* L.) were less hazardous (Grillo *et al.* 2014). The use of poly (epsilon-caprolictone) (PCL) as an atrazine carrier after encapsulation had no influence on the herbicide's long-term residual action on soybean as the mobility of atrazine was reduced, it resulted in a spectacular reduction in the phytotoxic accumulation of atrazine in soil, as well as increased herbicide activity (Pereira *et al.* 2014).

VARYING NANO FORMULATIONS AND WEED MANAGEMENT

Nano-encapsulation

Nano-encapsulation is the process of encapsulating solid, liquid, or gas nanoparticles (also known as the core or active) in a secondary substance (also known as the matrix or shell) to generate nano-capsules. Nano-encapsulation is a membrane-controlled method in which herbicides are coated with any semi-permeable membrane, which could be organic or inorganic. Chitosan, poly propylene, poly ethylene, poly styrene, poly vinyl alcohol, poly allylamine hydrochloride, poly sodium 4- styrene sulfonate, poly vinyl pyrolidone, starch, and others are some of the polymers used. Encapsulation of active ingredient (*a.i.*) is done by: indirect method of nanoencapsulation (IDM), direct method of nanoencapsulation (DM), solvent evaporation method (SEM) and nano spray method (NSM).

Herbicides can be encapsulated with nanoparticles to increase their efficacy by focusing at the unique receptor of a specific weed after entering the root system and inhibiting glycolysis, starving them to death.

Poly-å-caprolactone (PCL) nano capsules were utilised as carriers for three triazine herbicides, ametryn, atrazine, and simazine, and their stability and appropriateness for controlled release systems were evaluated. The nano capsules had an association effectiveness of roughly 84% and the nano-capsules were discovered to be stable. The in-vitro release investigations showed that the polymer chains relaxed, resulting in a regulated release. As a result, using PCL nano-capsules in environmental systems may be a potential strategy to improve herbicidal behaviour (Grillo *et al.* 2012).

The greater mortality of *Bidens pilosa* seedlings was observed even with a tenfold dilution (NC+ATZ at 200 g/ha) of PCL nanocapsules containing atrazine (NC+ATZ). The herbicide's long-term residual impact on soybeans was not improved by encapsulating it in poly-å-caprolactone (Preisler *et al.* 2018). The utilization of atrazine-containing PCL nanocapsules potentiated the post-emergence control of *Amarathus viri* and *B. pilosa* by the herbicide (Sousa *et al.* 2018) indicating the potentiality of nanoformulation as an efficient alternative for weed control. Most natural bioactive chemicals have a limited environmental half-life, which could be addressed via nanoencapsulation. This would enable for effective weed management with just one spray, lowering rates, costs, and threats to the environment. Furthermore, nanoencapsulation could allow for the simultaneous application of many substances while inhibiting interactions until they are released (Korres *et al.* 2019).

Nano-carrier

Herbicide nanocarrier research is primarily focused on decreasing the environmental impact of herbicides, specifically reducing herbicide non-target toxicity. A wide range of nanoparticles and materials are being used in the development of nanoparticle-based herbicides. The materials used include montmorillonite clay layers coated with a pH-dependent polymer (Han *et al.* 2010), core hollow shell manganese carbonate (Kanimozhi and Chinnamuthu 2012), nano-sized tubular halloysite and platy kaolinite (Tan *et al.* 2015), amino-activated iron (II, III) oxide magnetic nanoparticles (Viirlaid *et al.* 2009), and nanosized rice husks (Abigail *et al.* 2016). Some of the nanocarrier materials include: chitosan, tri-polyphosphate, alginate, poly -å-caprolactone, starch and rice husk

The zeolite Y surface changed with 1,1,3,3-tetramethyldisilazane (Zhang *et al.* 2006). Ion-exchange loading of paraquat in zeolite revealed a loading capability of 14% of the weight. The paraquat loaded with alginate/chitosan resulted in less herbicide leaching than paraquat alone with a two-hour delay in release time compared to the herbicide alone (Da Silva *et al.* (2013).

Chitosan/tripolyphosphate nanoparticles (NPs) with paraquat herbicide were less hazardous to crops and safe to use in weed management (Grillo *et al.* 2014). When sprayed pre-emergence, solid lipid nanoparticles containing both atrazine and simazine were found to be more effective in causing mortality of *Raphanus raphanistrum*, and when applied post-emergence, they were just as effective as the herbicide alone (De Oliveira *et al.* 2015). Imazapic and imazapyr herbicides were loaded onto chitosan nanoparticles to reduce their toxicity (Maruyama *et al.* 2016). Rice husk biochar was discovered to be an effective and environmentally friendly carrier for 2,4-D. The 2,4-D nano formulation based on rice husk biochar (DrBC) could operate as a herbicide carrier while also reducing herbicide leaching and providing long-term release abilities (Abigail *et al.* 2016)

The porous calcium carbonate was loaded by dissolving prometryn herbicide in ethanol and stirring it overnight. Herbicide could be held in the porosity to a maximum weight of 20% loading capacity and the composite showed 86 % prometryn release in 12 hours in aqueous solution, validated regulated release behaviour, and recorded 20 % greater efficacy in suppressing *Cynodon dactylon*. The composite demonstrated 3 times greater herbicide retention in the leachate test with the soil column than the control (Xiang *et al.* 2018).

Nano emulsion

Nano emulsions are emulsions that are nanoscale in size and are used to improve the delivery of active herbicidal substances. These are thermodynamically stable isotropic systems in which an emulsifying agent, such as surfactant and co-surfactant, is used to combine two immiscible liquids into a single phase. Nano-emulsion droplets are typically 20-200 nm in size. The nanoemulsion of pretilachlor microemulsion (ME) and monolithic dispersion (MD) was found to be much superior in managing *Echinochloa crus-galli* compared to the commercially available formulation (Kumar *et al.* 2016). At 1000 ìL/L, a nanoemulsion of *Satureja hortensis* L. essential oil totally reduced all growth characteristics of *Amaranthus retroflexus* (Hazrati *et al*. 2017). Even at a low dose of 0.05 wt %, nanoemulsions of *Foeniculum vulgare* essential oil completely inhibited the germination of *Phalaris minor*, *Avena ludoviciana*, *Rumex dentatus* L., and *Medicago denticulata* by affecting physiological processes such as membrane leakage and reactive oxygen species mediated cellular damage (Kaur *et al.* 2021).

Nano-adjuvants

There are commercially available herbicide adjuvants that claim to contain nanoparticles. Chandana *et al.* (2021) used a surfactant derived from nano-technology with a basis of soybean micelles to sensitise the crops resistant to glyphosate.

Nano-biosensors

Nano-biosensors can be used as a tool for detection of enzyme-inhibiting herbicides. The herbicide metsulfuron-methyl (an acetolactate synthase inhibitor) was detected in the soil using a novel nano-biosensor based on atomic force microscopy (Da Silva *et al*. 2013). Precision agriculture employs nanotechnology-based sensors to ensure the proper release of herbicide spray mixtures and precise control of herbicide applications. Herbicides could be used more effectively and efficiently with nano biosensors while being environmentally friendly (Duhan *et al.* 2017).

The advantages and limitations of nano formulations

The advantages of nano formulations include: phytotoxicity elimination or minimization; reduction of herbicides application rate per hectare and minimizing environmental pollution and CO_2 emission; enhanced soil herbicide residues mitigation; safety to the microbiota in the soil with encapsulated nano herbicides (Maruyama *et al.* 2016); enhanced efficacy of herbicides under rainfed agriculture due to slow-release nano formulations; greater selectivity against the target weeds; greater effectiveness against herbicide resistant weeds and improved quality of crop produce.

In addition to advantages, there are certain limitations of nano formulations which include: inhibition of seed germination, shoot, and root growth of crops like wheat, barley and onion by nanoparticles such as Ag, TiO2, and others; human health concerns as nanoparticles can easily enter the human body through the skin; environmental concerns as nanoparticles can persist in soil, water, and plants, posing a threat to human health. The greatest concern is the high production cost of nanomaterials.

Future research needs on nano formulations in India

India has a wide range of agroclimatic conditions and soil types. The highly diverse agriculture and farming systems are beset with different types of weed problems. Invasive alien weeds are a major constraint to agriculture, forestry and aquatic environment. Crop-specific problematic weeds (*eg:* weedy rice in rice) are emerging as a threat to cultivation, affecting crop production, quality of product and income of farmers. Traditionally, weed control in India has been largely dependent on manual weeding. However, increased labour scarcity and costs are encouraging farmers to adopt labour and cost saving option of herbicides usage. The efficacy of herbicides used for weed management can be enhanced through the application of nanoherbicides in agricultural fields. Encapsulation of herbicides in nanomaterials minimizes the loss of herbicide along with its sustained release and increased specificity toward target weed. Several polymeric nanoparticles, nanocapsules, and nanospheres are used as carriers for herbicides. Polymers such as alginate, chitosan, pectin, poly(epsilon-caprolactone), poly (methyl-methacrylate), and poly (lactic-*co*-glycolic acid) are considered as ideal nanocarriers for several herbicides such as paraquat, 2,4-dichloro-phenoxyacetic acid, diuron, ametryn, atrazine, and simazine, whereas other nanocarriers such as rice husk nanosorbents, mesoporous silica nanoparticles, and nanoclay can be applied for fabrication of nanoherbicides. Nanoherbicides are effective against a variety of weed species in India some of which include *Echinochloa crus-galli*, *Chenopodium album*, *Bidens pilosa*, *Amaranthus viridis*, and *Raphanus raphanistrum* (Ghosh *et al.* 2022).

Nanoherbicidal formulations under development in the current decade could be a new strategy to address all the problems caused by the conventional herbicides. The potential use of nanostructured materials enables the use of herbicides effectively and rules out the emergence of weed resistant population at an early stage. Newer weed management approaches must be developed considering the threat of HR weeds appearance in addition to the recurrence and persistence of weeds and the need to bring down weed management costs to enhance profit for farmers while protecting the environment.

A few research areas that need to be focused in this regard include: assessment of long-term effect of nano-herbicides on plant system, soil organisms and ground water. Significant research efforts should be made to develop nano bio formulations using plant extracts, fungal nanotechnology or myco-nanotechnology, for evolving efficient and ecologically friendly weed management approaches. The fate of nano- herbicides in soil and plant system, behavior, routes of uptake and entry into the atmosphere has to be evaluated. Systems that enhance the release profile of nano-herbicides without altering their characteristics with less environmental damage should be developed. Weed Identification tool kit with nanoparticles has to be designed. Broad spectrum weed based nano formulations and i*n situ* low-cost herbicide residue estimation procedures should be formulated.

Conclusion

In the present agricultural scenario, herbicides are widely used in weed management to improve agricultural production leading to adverse impact on soil, water and food resources and alternative techniques must be evolved to manage weeds effectively with lesser environmental impact. The nanotechnology has potentiality to revolutionise agriculture. It will boost crop output by reducing the quantity of herbicides used, which will indirectly reduce environmental pollution. Greater research efforts need to be carried out for nanotechnological solutions in weed management and for their wide adoption in agricultural systems of India.

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