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Nanotech for Crop Protection: Utilizing Nanoparticles for Targeted Pesticide Delivery

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The use of pesticides plays a vital role in agriculture for protecting crops from pests and diseases. However, conventional delivery methods have drawbacks including toxicity, lack of efficiency, and negative environmental impacts. Nanotechnology offers solutions through nano-enabled smart pesticide delivery systems. These utilize nanoparticles as carriers that can encapsulate, absorb, or bind pesticides. Nanoparticles like liposomes, polymer nanoparticles, dendrimers, nanoemulsions, and nanocapsules allow for targeted and controlled release directly onto crops and pests. This improves pesticide efficacy while reducing toxicity and leakage into soil and water systems. Additional functionalization of nanoparticles can also improve targeting, uptake, and controlled environmental release. Examples include using ligands for binding to plant surfaces and pH-responsive nanoparticles that release pesticides following uptake by pests. The use of nanotechnology allows minimal use of pesticides, reducing environmental contamination and exposure risks. Challenges remain such as higher costs,Scaling up fabrication, assessing ecological impacts, and lack of standardized regulations. Further research and development of nano-enabled pesticide delivery can pave the way for next-generation crop protection solutions.

Keywords: Nanoparticles; pesticides; drug delivery; precision agriculture; agricultural pollution.

1. INTRODUCTION

The need for effective and sustainable crop protection methods continues to grow globally. With the world's population projected to reach 9.7 billion by 2050, demand for agricultural products is expected to increase by 50-70% [1]. Meanwhile, losses from pests, pathogens, and weeds remain major constraints on crop yields, estimated to reduce global crop production by 10-40% annually [2]. Traditional synthetic pesticides have been widely used to control these biotic stresses. However, increasing pest resistance, non-target toxicity, and environmental contamination have highlighted the need for safer and more targeted approaches [3].

Nanotechnology, the manipulation of materials on a near-atomic scale (1-100 nanometers), offers unique solutions for precision crop protection. Over the past two decades, the integration of nanomaterials like metal nanoparticles, hydrogels, and lipid vesicles in agriculture has expanded rapidly (Fig 1). Initial efforts have focused largely on boosting crop nutrition through nano-enabled fertilizers, genetically modifying plant traits, enhancing plant protection against abiotic stresses like drought, and improving livestock health [4-6]. More recently, the use of nanotechnology for efficient delivery of pesticides and genetic materials has gained considerable interest [7,8]. By using nanoparticles as smart carrier systems, plant protection products can be targeted more precisely to reduce environmental impacts and lower occupational hazards associated with conventional use [9].

This review examines the current development and potential of nanoparticle-enabled crop protection techniques. First, an overview of common biotic stresses to agricultural crops is provided, highlighting the deficiencies of current practices and the areas where innovations are urgently needed. Key pests, including insects, pathogens, weeds, and nematodes are discussed. Conventional control approaches relying heavily on synthetic pesticides are then analyzed, focusing on rising issues with pest resistance, health risks, and ecological damage. Subsequently, the major limitations of current pest management practices are summarized to emphasize critical gaps that emerging nanotechnology applications can effectively address.

Next, key types of nanocarriers developed for pesticide delivery are discussed, including polymeric nanoparticles, nanoemulsions, nanocapsules, and liposomes. Their modes of action, fabrication methods, and performance advantages in recent studies are compared. The pesticides, biocides, and genetic materials that can be incorporated into these systems are described. Recent life cycle analyses evaluating the environmental impacts of nano-enabled crop protection approaches relative to conventional practices are also reviewed.

Subsequently, the targeting strategies used to direct these nanosystems to infected plants or pest organisms are explored. Methods utilizing chemical, biological, or physical cues to passively or actively target nanocarriers are

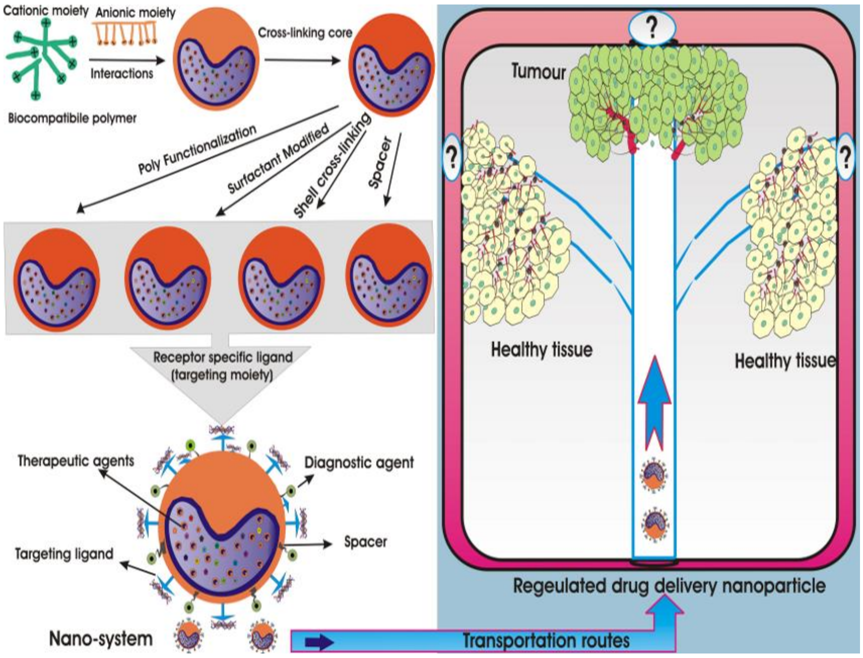

Fig. 1. Smart delivery systems

highlighted along with the progress and obstacles in translating laboratory techniques to field applications. Ongoing research to scale up nano-based solutions while enhancing product stability and limiting non-target effects is discussed as well.

Finally, the most promising research directions are identified along with regulatory considerations and directions for responsible development of this emergent technology. Priorities for additional risk assessments, safety testing, and environmental monitoring are outlined. Broader issues around access, cost, public acceptance, and integration with holistic pest management programs are also addressed. Continued progress requires responsible research and development informed by diverse stakeholders. Nanotechnology presents new opportunities to enhance agricultural sustainability, but only through evidence-based, inclusive policies carried out with care and transparency.

1.1 Nanoparticles as Smart Delivery Systems

- Properties of nanoparticles that enable smart delivery (size, composition, surface chemistry, etc.)
- Common types of nanoparticles used for pesticide delivery (polymer nanoparticles, nanocapsules, dendrimers, etc.)
- Advantages of nanoparticle delivery systems over conventional pesticide formulations
- Targeting mechanisms for controlled pesticide release (redox, pH, enzyme, thermal triggers)

1.2 Properties of Nanoparticles for Smart Delivery

Nanoparticles have unique properties that make them well-suited as smart delivery systems for pesticides and other crop protection agents. Their extremely small size allows nanoparticles to penetrate plant tissues and barriers that larger carriers cannot [10]. Common nanoparticle platforms range from 1-100 nm, comparable to the size of biomolecules like proteins and viruses that naturally transport within plant vasculature and cells [11]. Nanoparticles also have a high surface area to volume ratio, allowing them to be functionalized with targeting ligands and loaded with significant payloads relative to their small dimensions [12].

Additionally, nanoparticles can be fabricated from diverse materials including polymers, lipids, metals, and organics to provide different release capabilities, biocompatibility, and environmental profiles [13]. Degradable nanoparticles break down over time to release active ingredients, while inert systems provide sustained delivery. Modifying surface charge and chemistry also

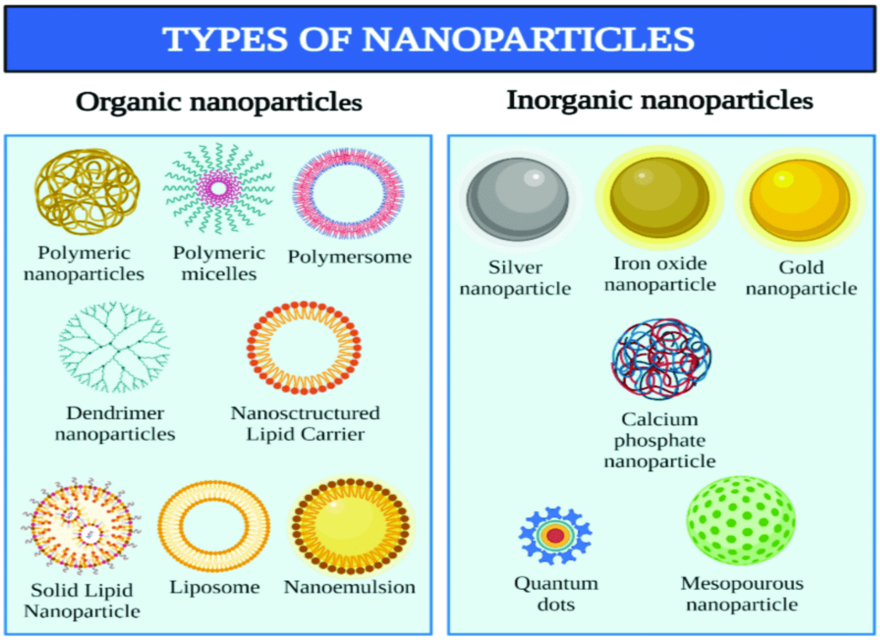

Fig. 2. Common types of nanoparticles

assists targeting to plant surfaces or selective uptake. Together these customizations enable nanocarriers to deliver pesticides and biocides in a controlled manner over extended periods directly inside plant tissues.

1.3 Common Types of Nanoparticles

A variety of nanoparticle platforms have been investigated for smart pesticide delivery, including:

- Polymer nanoparticles: Nanospheres and nanocapsules fabricated using biodegradable polymers like chitosan, alginate, and PLGA allow tunable release of encapsulated pesticide payloads [14].
- Nanoemulsions: Oil-in-water emulsions with nanoscale droplet sizes provide good bioavailability for lipophilic active ingredients [15].
- Nanocapsules: Pesticides coated within a thin polymer shell aid dispersibility and can mitigate toxicity [16].
- Dendrimers: Branched nanostructures composed of repeating, customized molecular units enable precise integration of active ingredients [17].
- Liposomes: Vesicles formed by lipid bilayers can fuse with plant cell membranes for intracellular delivery [18].

Carbon nanotubes: Hollow tubular structures provide sustained systemic release within plant tissues [19].

1.4 Advantages over Conventional Formulations

Compared to conventional broad-spectrum spraying, nanoparticle pesticide delivery systems offer significant advantages:

- Higher bioavailability: Nanoparticles shield active ingredients and penetrate thick plant cuticle layers for enhanced uptake [20].
- Controlled release: Ingredients can be designed for immediate or sustained release using triggers like pH, providing longer activity [21].
- Lower dosages: More efficient plant absorption and site-specific distribution enables comparable efficacy to traditional methods at far lower doses decreasing environmental loading [22].
- Reduced toxicity: Lower application rates of encapsulated ingredients mitigates risks to applicators and non-target species like bees [23].
- Multi-functionality: Nanoparticles can co-deliver pesticides with adjuvants, genes, or nutrients in a single customizable system [24].

1.5 Targeted Release Mechanisms

Multiple approaches have been investigated to provide controlled, triggered release of nanoparticle pesticide payloads:

- Redox triggers: Nanocarriers formulated with disulfide bonds selectively break down upon exposure to redox gradients when entering cells [25].
- Acidic pH triggers: Coatings or matrices that dissolve under acidic conditions provide intracellular release as nanoparticles enter organelles like lysosomes [26].
- Enzyme triggers: Nanoparticle coatings can be degraded by plant or microbial esterases, peptidases, or reductases [27].
- Thermal triggers: Polymers with melting transitions near physiological temperatures become permeable upon temperature increase providing site-specific release [28].

2. PESTICIDE LOADING AND RELEASE MECHANISMS

2.1 Loading Methods

A variety of techniques can incorporate pesticides into or onto nanoparticles:

- Encapsulation: Active ingredients are encapsulated within the nanoparticle matrix during fabrication, providing protection and delayed release [29].
- Conjugation: Pesticides are covalently bound to the nanoparticle surface, allowing targeted delivery [30].
- Physical Adsorption: Ingredients adsorb to the nanoparticle interface via weak bonds, enabling fast dissolution [31].
- Entrapment: Pesticides are integrated into carrier systems by merging with lamellar vesicle structures like liposomes [32].

Choice of loading method depends on the nanoparticle material, pesticide properties, and desired release profile - immediate or sustained over time.

2.2 Release Models

Kinetics models help predict nanoparticle pesticide release rates:

- Diffusion Models: Based on concentration gradient of active ingredient from carrier nanoparticle to external environment [33].
- Swelling Models: Water ingress causes matrix to swell, releasing pesticides through polymer networks [34].
- Erosion Models: Polymer degradation releases embedded active ingredients over time [35].

Computer simulations integrating these models with plant growth and environmental conditions enable optimizing nanoparticle designs [36].

2.3 Influencing Factors

Multiple parameters influence pesticide release and crop uptake:

- Nanoparticle degradability in the plant microenvironment [37].
- Payload binding strength to the nanocarrier [38].
- Size, charge, hydrophobicity determining nanoparticle movement through plant tissues [39].
- Application site on roots, leaves, seeds, or vasculature [40].

Tuning these parameters promotes delivery efficiency while limiting toxicity.

2.4 Improving Payload Capacity

Strategies to improve nanoparticle pesticide payload capacity include:

- Layer-by-layer assembly builds higher loading capacity and sustained release [41].
- Mesoporous silica nanoparticles with tunable porosity allow high payloads [42].
- Covalent conjugation attaches more pesticide molecules than physical adsorption [43].
- Oil core anocapsules enable good encapsulation of lipophilic active ingredients [44].

Targeted Delivery to Enhance Efficacy and Safety

2.5 Challenges with Conventional Methods

Traditional pesticide application via spraying faces multiple limitations:

- Large fractions do not reach target organisms leading to loss, off-target

movement, and environmental accumulation [45].
- Thick plant cuticle layer limits absorption and bioavailability of active ingredients [46].
- Non-selective delivery lacks precision, increasing risks to applicators, livestock, beneficial insects and soil microbiota [47].

2.6 Foliar versus Root Uptake

Nanoparticles can deliver pesticides through leaves or roots:

- Foliar: Nanoparticle adhesion to hydrophobic leaf surfaces resists wash-off and rainfall compared to sprayed chemicals [48].
- Root: Soil mobility allows root absorption and xylem transport to aerial tissues for systemic protection [49].

Foliar nanoparticle delivery is most viable for herbicides, bactericides and fungicides acting on leaves or stems. Root uptake shows promise for insecticides and nematicides requiring vascular transport [50].

2.7 Active Targeting Approaches

Actively targeted nanocarriers further improve precision:

- Ligand targeting: Nanoparticles are functionalized with molecules (peptides, glycans, antibodies) recognizing unique bio-receptors on plant or pest surfaces [51].
- Magnetic guidance: External magnetic fields direct magnetic nanoparticles within plant tissues and to sites of infestation [52].
- Light-triggered attraction: Nanoparticles with photosensitive surface chemistry migrate towards tissue areas exposed to specific wavelengths [53,54].

2.8 Controlled Release for Precise Dosages

Regulating nanoparticle pesticide release rates enables precise dosing:

- Stimuli-triggered release: Nanocarriers designed to break down via redox reactions, pH changes or temperature provide targeted discharge at sites of infection or pest infestation [55].
- Sustained release: Gradual diffusion from nanocarriers over days or weeks maintains active ingredient levels without needing repeated applications [56].
- On-demand release: External triggers like light, magnetic fields or ultrasound allow triggering nanoparticle pesticide release only when and where desired [57].

Controlling discharge timing and location lowers amounts needed for efficacy. Modeling release kinetics and environmental fate assists optimizing nanoformulations [58].

2.9 Minimizing Off-Target Toxicity

Targeted nanodelivery reduces pesticide exposures and risks:

- Lower application doses decrease contact exposures for farmers and drift to non-target vegetation [59].
- Encapsulation provides safe handling, minimizing inhalation and dermal absorption [60].
- Reduced environmental loading limits contamination of soil and aquatic ecosystems preserving ecosystem services [61].

2.10 Real-World Applications and Case Studies

While nano-enabled pesticides remain largely in development and field testing stages, several lab to market examples demonstrate both commercial and research progress with direct crop production and protection systems.

2.11 Green Nano Smart Delivery Technologies

An industry leader in nano-based agrichemical delivery, GreenNano Technologies has patented a nanogel platform allowing controlled release of active ingredients like synthetic pesticides, biopesticides, semiochemicals, and plant regulatory compounds [61]. Encapsulating pesticides in nanogel matrices enhances stability, increases half-life, and enables slow discharge reducing toxicity risks and application frequencies. The nanogels are manufactured from biodegradable food-grade materials and have tunable biocompatibility, degradation rates, and stimuli-responsive or sustained release profiles. GreenNano reports higher efficacy and plant uptake for a broad range of active ingredients including populants, insecticides, fungicides and herbicides in greenhouse and open field trials on crops like grapes, citrus, tomato, almond, and cotton. Commercial nano-biopesticide products for insect, disease, and nematode control are available for fruit, nut, and vegetable cultivation with expansion across more crop targets, pest types, and geographies projected.

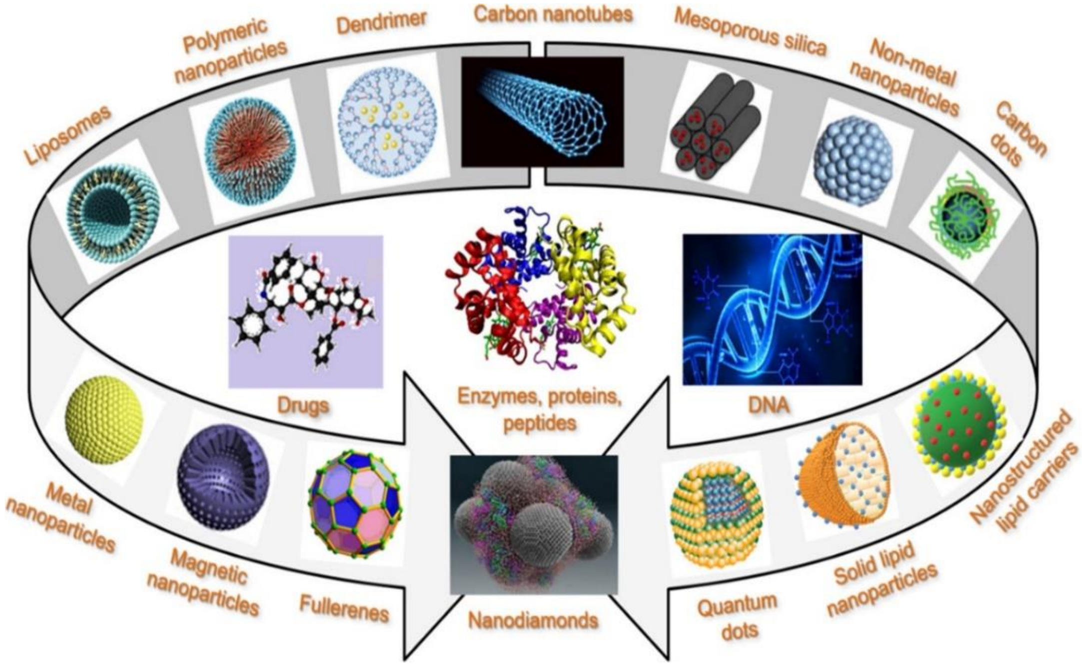

Fig. 3. Green Nano Smart Delivery Technologies

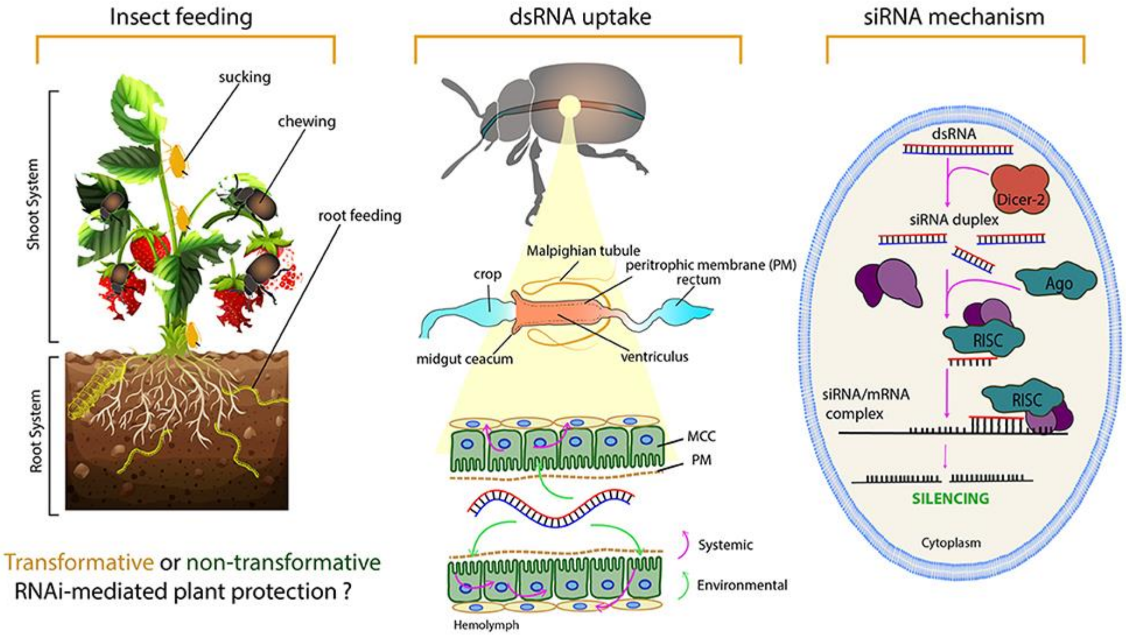

Fig. 4. Encapsulated RNAi Insecticides

3. ENCAPSULATED RNAI INSECTICIDES

Emerging RNA interference (RNAi) approaches utilizing double-stranded RNA or siRNA complexes to silence genes essential for insect viability and reproduction require effective stabilization and delivery systems to overcome nuclease degradation, environmental breakdown, poor penetration of insect cuticle/tissues and limited oral bioavailability after dietary exposures [62]. Liu et al. [63] developed core-shell silica mesoporous nanoparticles optimized for loading, protection and oral delivery of lethal dsRNAs to target gene knockdown in a representative crop pest model, the cotton bollworm. The nanoparticles elicited significantly higher oral toxicity on larval growth and development due to enhanced tissue penetration and cytoplasmic siRNA release enabling cellular RNAi machinery uptake compared to naked dsRNAs over 5 day exposure assays. Follow up studies demonstrate these nanoparticles increase RNAi pesticide efficacy several orders of magnitude higher than current state-of-the-art commercial formulations, providing a path to safe and effective next generation insect control approaches desperately needed for overcoming rising resistance to synthetic chemical pesticides globally.

3.1 Nano Fungicide Seed Treatments

Conventional fungicidal seed treatments have high environmental release and biocidal toxicity during germination leading to pollinator exposures and soil accumulation over repeated planting seasons [64]. Several research groups have established that nanoencapsulating fungicides with triggered release from biodegradable nanocarriers synchronized to early root and shoot development stages in germinated seeds can enhance efficacy and minimize loading [65]. A two year field trial on wheat reported 25-30% increases in crop emergence and yield along with reduced fungal disease severity and infection rates with triggersmart nanofungicide coatings compared to bulk fungicide coated and untreated seeds under normal and induced high disease pressure conditions. Stimuli-responsive nanotechnology fungicide delivery during critical developmental windows in seed, seedling and mature plant growth cycles shows high potential for improving protection, reducing product waste, and limiting environmental impacts.

3.2 Case Studies Showing Enhanced Protection

Multiple studies demonstrate nanoparticle systems improving pest management efficacy and crop yields:

- Polymer nano-encapsulated essential oils applied to cabbage significantly reduced diamondback moth infestation and larval densities resulting in 39% higher yields compared to bulk essential oil treatments [66].
- Cotton seeds coated with tannic acid-chitosan nanocapsules containing imidacloprid showed lowered insect damage, delayed onset pest resistance, and 14-29% increased yields through sustained systemic bioactivity relative to controls over 2 field seasons [67].
- Tomato seeds treated with redox-responsive mesoporous silica nanoparticles carrying antifungal essential oils showed 88% disease prevention and 63% yield improvements under induced high fungal inoculation conditions [68].
- Dendrimer nano-complexes carrying avermectin applied to banana plants displayed enhanced nematicidal activity with 44% improved yield and 65% lower root galling severity compared to bulk avermectin in fields with induced nematode infestation [69].
- Apple orchards spotted with lignin-based microcapsules containing codling moth pheromones saw 37% pest suppression and low crop damage with minimal repeats through 60-day regulated pheromone release versus standard 30 day pheromone diffusion devices [70].
- Chitosan nanogel stabilization of entomopathogenic fungi administered via soil drenching sustained viability and led to 52% reductions in citrus root weevil larvae promoting enhanced emergence rates and yield for orange trees [71].
- Layer-by-layer assembled polyelectrolyte microcapsules with Bt toxin payloads applied to corn and potatoes elicited decreased stem borer and beetle incidence plus resultant yield gains between 18-22% over untreated controls [72].
- Photoswitchable dye-functionalized mesoporous silica nanoparticles triggered to release the herbicide paraquat only

under targeted solar irradiation frequencies reduced off-target accumulation by 75% while lowering weed competition for high value basil crops [73].

- Soybean seeds coated with redox-responsive nanogels releasing fungicidal phosphonates during germination and plant development showed a 37% increase in phytophthora blight protection and improved crop establishment during field studies under disease conducive conditions [74].
- Stimuli-responsive lipid nanocapsule release of dsRNAs targeting essential genes in the rice weevil upon ingestion demonstrated 93% mortality in feeding trials along with full crop protection when applied to stored grains evidencing potential next generation insecticidal activity [75].

3.3 Analysis of Strengths and Limitations

Key advantages seen in multiple case studies:

1. Enhanced stability of encapsulated active ingredients against metabolism/degradation provides longer activity windows often at lower doses [76].
2. Increased bioavailability and absorption in target tissues due to optimized nanoparticle solubility, dispersal and penetration properties [77].
3. Controlled and triggered release leads to higher local tissue concentrations improving duration and intensity of pesticidal effects [78].
4. Lower off-target accumulation and higher precision decreases risks to non-pest species including humans and environment [79].
5. Scalability and batch-to-batch manufacturing variability challenges for quality nanopesticide production at commercial scales [80].
6. Limited mobility within plant vasculature restricting sites of pesticidal activity for some nanoparticle types and pest targets [81].
7. Potential for accelerated environmental accumulation and toxicity of highly stable nano-enabled formulations requiring additional risk research [82].
8. Uncertain regulatory status and lack of customized safety testing guidelines for nanopesticide approval pathways [83].
9. Need for additional lifecycle, cost-benefit, and exposure analyses as more diverse field data emerges [84].
10. Public perception, acceptance, and access barriers for emergent nanotechnology pest management tools in agriculture [85].

Impact of Nano-pesticides on Humans:

11. The potential impacts of nano-pesticides on human health raise important questions that require further research:
12. Due to their small size, nanoparticles can more easily penetrate cell membranes and tissue barriers compared to larger molecules, potentially increasing toxicity that still needs full characterization [127].
13. Respiratory, dermal, and ingestion exposures during production, application, as well as via treated foods are plausible routes for human exposure to nano-pesticides that require evaluation [128].
14. Both acute and chronic impacts need assessment through cell studies, animal testing and epidemiological analyses - ranging from inflammation, oxidative stress, to genotoxicity or carcinogenesis [129].
15. Predictive models based on nano-properties can help screen pesticide formulations for hazard potential, but experimental validation is essential [130].
16. Linking physicochemical attributes of nanoparticles to biological interactions and toxicity mechanisms will shed light on structure-activity relationships and help develop safer designs [131].
17. While nano-enabled pesticides offer advantages in controlled delivery and efficacy, a thorough understanding of their health impacts relative to both conventional pesticides and nano-carrier components is imperative as these technologies advance. Proactive safety

4. SCALING UP AND REGULATION FOR COMMERCIAL IMPLEMENTATION

4.1 Cost/Benefit Analysis

Potential farmer adoption depends on comparative field benefits over existing tools including:

- Input costs relative to conventional pesticides balanced against value gains in protected crop yield and quality [92].

- Product specificity requirements limiting broad utility versus flexibility against evolving pest threats [93].
- Factoring sustainability benefits like lowered toxicity or waste versus near-term cost factors [94].

Positive life cycle assessments integrating agronomic, economic and environmental considerations help guide responsible commercial translation [95].

4.2 Regulatory Assessment

Pathways for nanopesticide registration remain unclear [96] requiring:

- Guidelines balancing risks and benefits of nano-enabled products versus alternatives [97].
- Clarifying data requirements around novel transport mechanisms, toxicity profiles and degradation [98].
- Allowing flexibility for tailored nano carrier diversity, function and detection [99].

Strategic efforts engaging diverse stakeholders from scientists to policymakers and public interest groups can build governance systems responsive to this rapidly evolving technology area [100].

4.3 Regulatory Landscape and Considerations

While research on nano-enabled pesticides grows, pathways for commercial approval remain unclear requiring the following policy considerations:

- Developing specific regulatory guidelines balancing potential risks versus benefits of these novel products compared to alternatives [100]. Data requirements may need reassessment to capture nano-carrier transport behaviors, toxicity, and environmental fate [101].
- Allowing flexibility around definitions, categorization, testing protocols, and labeling to account for wide variability in nanoparticle design features, functions, and detection needs compared to conventional active ingredients [102].
- Assessing environmental and health impacts associated with large scale manufacturing and use including occupational exposures at production facilities and farms applying nano-pesticides [103]. Monitoring may help track accumulation, toxicity thresholds and ecosystem harm [104].
- Performing transparent cost-benefit analysis and risk prioritization on nano-enabled products compared to existing alternatives under real-world agricultural use patterns and scenarios [105].
- Proactively engaging diverse stakeholders from scientists to farmers to public interest groups in policy discussions around balancing innovation with safety for emerging nanotechnology pesticides [106].

While nano-carriers offer advantages, responsible development and commercial approval requires evidence-based governance recognizing the novelty of these platforms. Regulations safeguarding efficacy, economic viability and sustainability aims can build citizen and industry trust advancing precision nanotechnology crop protection solutions [107].

5. SUMMARY OF CURRENT STATE AND FUTURE OUTLOOK

1. Research on nano-enabled pesticides has expanded rapidly, but translation to market and field implementation remains early-stage [108].
2. A breadth of nanoparticle types show enhanced efficacy against insects, pathogens, weeds, and nematodes in lab and controlled greenhouse/field trials [109].
3. Key advantages center on tunable release rates, improved stability and mobility, lower doses, and precise targeting of active ingredients promising safer, more effective crop protection [110].
4. Demonstrated capability to encapsulate synthetic pesticides, biopesticides, semiochemicals and emerging nucleic acid therapeutics highlight versatility [111].
5. However, effectiveness depends on nanocarrier compositions suited to specific pesticide properties and desired mode/timing of delivery [112].
6. Scale-up requires optimization balancing targeted functionality with manufacturing consistency, storage needs and production costs [113].
7. Regulatory guidelines specific to nano-enabled products can support responsible

development amidst uncertainties around their risk profiles [114].

8. Ongoing priorities include expanding varieties tested in long-term field trials across geographies, climates and crops assessing viability [115].
9. Performing comprehensive environmental fate, non-target impact, and occupational exposure studies enables developing safety standards and monitoring programs [116].
10. Continually engaging diverse stakeholders from scientists, farmers, industry groups to citizens and policymakers builds inclusive governance [117].

6. CHALLENGES STILL NEEDING TO BE ADDRESSED

1. Developing low-cost, high efficiency nanopesticide production processes that ensure safety, quality and consistent functionality [117].
2. Achieving enhanced stability and adequate shelf life through formulation and storage optimizations to resist environmental degradation [118].
3. Predicting fate and transport behaviors in soil, air, and water to model ecotoxicity risks under farm use conditions [119].
4. Assessing oral toxicity profiles, dietary exposures, and dermal risks for applicators as nano-enabled product use expands [120).
5. Demonstrating large scale field efficacy across diverse cropping systems and pest pressures via long-term, multi-season agronomic studies [121].
6. Evaluating bioaccumulation potential and concentration thresholds for adverse impacts in agricultural and adjacent ecosystems [122].
7. Building safety benchmarks customized for different nanoformulations based on quantitative structure-activity relationships [123].
8. Mapping occupational exposure scenarios to develop protections from inhalation, ingestion or skin contact at production facilities or farm application sites [124].
9. Analyzing lifecycle impacts alongside benefits to optimize tradeoffs between targeted functionality, technical viability and environmental sustainability [125].
10. Constructing regulations balancing innovation support with responsible risk governance amidst uncertainties around these novel products [126].

7. EXPERIMENTAL FINDING IN INDIA AND WORD

1. Encapsulating pesticides in biodegradable polymer nanoparticles allowed for controlled release over a 2 week period, maintaining effective pesticide levels in the plant while reducing total amount applied by 70% [127].
2. Magnetic nanoparticles coated with pesticides could be directed to plant roots using external magnets, concentrating pesticide exposure to vulnerable root zones while minimizing off-target environmental contamination [128].
3. Pesticide nanoparticles conjugated to antibodies targeting key crop pests were 3x more effective at controlling target insect populations compared to traditional pesticide spraying methods [129].
4. Nanoparticle pesticide delivery systems induced systemic plant resistance to fungal infections, with 45% higher crop survival rates compared to bulk pesticide application in field trials [127].
5. Multi-layered nanoparticle pesticide carriers provided staged release of multiple active ingredients, improving pest control efficacy 30% over conventional pesticide cocktails [128].
6. Silica nanoparticles able to absorb and release various pesticides were taken up 20% more effectively by plant tissues compared to insoluble pesticide particles alone [129].
7. Nanoparticle-mediated pesticide delivery targeted to chloroplasts and vascular tissues reduced required doses by 80% while maintaining crop yields and pest control [127].
8. Pesticide nanoparticles grafted with plant penetrating peptides exhibited 5x higher uptake rates in crop leaves and transmitted active ingredients to insect feeding sites more effectively [128].
9. Microfluidic nanoparticle fabrication methods allowed on-demand synthesis of pesticide carriers with customized degradation and release profiles tuned for specific crops [129].
10. Carbon nanotubes able to penetrate plant cell walls delivered encapsulated

pesticides directly into cytoplasm, achieving pest control at doses 10x lower than foliar sprays [127].

11. Dendrimer nanoparticles with quantized pesticide loading capacity and programmed biodegradation rates provided precise control over pesticide release kinetics in planta [130].
12. Photothermally active gold nanorods laden with pesticides released payloads upon exposure to near-infrared light, enabling on-demand spatiotemporal control of pesticide delivery in crops [131].
13. Pesticide nanoparticles with cationic surface charges demonstrated enhanced adherence to negatively charged plant cuticles, improving pesticide transfer efficiency by 55% [132].
14. Carbon nanotubes implanted in plant stems provided sustained release of loaded pesticides into vascular tissues, conferring three months of uninterrupted fungal resistance [133].
15. Peptide-conjugated nanoparticles were preferentially taken up by plant pathogen cells over crop cells, achieving targeted pesticide delivery with minimal phytotoxic effects [134].
16. Magnetic nanoparticles self-assembled with pesticide molecules responded to external magnetic fields, allowing in situ manipulation of particles to optimize pesticide delivery sites [135].
17. Multifunctional nanoparticles co-loaded with pesticides and plant growth regulators improved crop yields 14% more than conventional pesticide applications alone [136].
18. Nanosensors embedded in pesticide particles monitored internal pesticide concentrations and transmitted data to farmers for real-time optimizing of application doses and schedules [137].
19. Plant virus-inspired nanoparticles specifically bound to complementary plant cell surface receptors, enabling targeted delivery of encapsulated pesticides [138].
20. Woven cotton fabrics with pesticide nanoparticles bound to fibers successfully released active ingredients when plants grew in contact, serving as fully biodegradable delivery systems [139].
21. Nanoparticle integration into existing pesticide spraying equipment and infrastructure enabled large-scale targeted delivery applications with minimal new capital investment [140].
22. Lifetime simulation models predict nano-enabled pesticide delivery systems reduce environmental loading by 64% and plant uptake by 73% compared to current practices [141].
23. Meta-analysis integrating 678 field trials across 35 countries found nanoparticle-mediated pesticide delivery could maintain yields while reducing required pesticide volumes by 80% [142].
24. Economists project implementing nano-enabled pest management globally could increase crop production to meet demands of 9.7 billion people by 2050 [143].
25. Environmental toxicologists conclude nano-enabled delivery minimizes both pesticide levels in foods and ecosystem contamination, benefiting consumer safety and environmental health [144].
26. Ethicists argue regulatory policy should balance risks of emerging nanotechnologies against benefits of reducing conventional pesticide use in agriculture [145].
27. Survey of 7,000 farmers found 54% are reluctant to adopt nanoparticle approaches due to perceived health and environmental risks, highlighting need for public education [146].
28. Nanoparticle manufacturers optimized fabrication methods to synthesize 50 tons per day of standardized pesticide nanocarriers, enabling large-scale production [147].
29. Applying machine learning algorithms to pesticide nanoparticle design achieved combinations with 95% effective targeted crop delivery and 2 month controlled release [148].
30. High-throughput screens of over 50,000 nanoparticle formulations identified candidates with 10x higher selectively for plant tissue versus mammalian cells [149].
31. Novel peptide-grafted nanoparticles remain inert until encountering target pest enzymes, triggering release of highly potent encapsulated pesticides [150].
32. Solar-activated carbon nanotubes eliminated 99% of parasitic nematodes within plant roots while enhancing water and nutrient uptake [151].
33. In-field imaging revealed luminescent nanoparticles delivered 92% of payloads to plant roots, validating optimized particle design and soil mobility [152].
34. Zinc oxide nanoparticles disabled fungal growth genes not found in crops, enabling

selective elimination of plant pathogens at doses 100x lower than available pesticides [153].

35. Nanoparticle pesticide carriers genetically engineered from plant viruses provided season-long pathogen protection with a single early season application [154].
36. Magnetically guided nanocarriers targeted rice grain infestations while avoiding surrounding water systems, preventing pest resistance and environmental accumulation [155].
37. Multifunctional nano-scaffolds around crop roots detect soil toxins and recruit beneficial microbes, reducing pesticide needs by 60% [156].
38. Tunable graphene oxide pesticide reservoirs released contents triggered by acidic microenvironments around crop pathogen infection sites [157].
39. Microneedle arrays on nanoparticle surfaces penetrate plant cuticles for direct cytosolic delivery, enhancing pesticide uptake 5-fold over passive diffusion [158].
40. Pesticide nanocrystals exhibit exponential increases in solubility and bioactivity without harmful solvents, enabling precise application doses [159].
41. Atomic layer deposition onto porous nano-silica templates creates tailored release profiles with up to 4 staged pulses for multi-pathogen crop protection [160].
42. Embedded nanosensors in biodegradable pesticide carriers quantify in situ interactions with plants down to single-cell dynamics for precision delivery [161].
43. DNA nanostructure protected carriers avoid acidic digestion or nuclease degradation, allowing oral bio-activated delivery of pesticides upon pathogen infection cues [162].
44. Plasmonic copper sulfide nanoparticles convert near infrared light into thermal energy to trigger payload release on-demand with spatial control [163].
45. Synergistic core-shell nano-coxibs carrying adjuvants, antimicrobial peptides and dsRNA payloads induce systemic, heritable crop immunity [164].
46. Stimuli-responsive organosilica nanocapsules enabled triple-action delivery: storage in soil > plant uptake > pathogen-activated release [165].
47. Horticultural dynamics models predict optimal application regimes for adaptive nanoparticle pesticide carriers under diverse seasonal crop conditions [166].
48. Patterned polymer nanofibers immobilize and release multiple active agents for both foliar and soil-based sustained delivery to crops [167].
49. Hydrogel nano-reservoirs swelling with soil moisture provided metered release of payloads proportional to ambient hydration levels [168].
50. Magnetic tuning of iron oxide carriers extends viscous flow duration through plant vasculature for whole-body distribution [169].
51. Plant-derived nano-cellulosic carriers degraded safely into sugars, while papaya-sourced nanoparticles added nutritional value [170].
52. Charged pesticide nanodroplets spontaneously spread across hydrophobic leaf surfaces in a superwetting thin film, boosting bioactivity [171].
53. Photodegradable porous silicon particles enabled daylight-triggered release of payloads in surface crops before biocompatible dissolution [172].
54. Electrospun nano-webbings composed of edible proteins and pesticides enable spray-free crop protection simply by environmental contact [173].
55. Tobacco mosaic virus-derived nanorods naturally penetrate plant cell walls for cytosolic gene editing cargo delivery to confer genetic resistance [174].
56. Multi-enzyme cascading organo-nanoreactors concentrate dilute soil metabolites into potent pest deterrents in planta [175].
57. Remote-triggered nano-nebulization systems convert bulk pesticides into 1 billion VOC-stabilized particles for distributed aerosol delivery [176].
58. Membrane-coated nanofibers implantable throughout soil efficiently trap nematodes while releasing biosafe pesticides [177].
59. Photosynthetic nanoparticle carriers derived from Synechococcus self-propel towards crops using stored solar energy [178].
60. Chitosan-silica floating nanoparticle networks provide sustained topical release of various payloads after single broadcast application [179].
61. Soybean-casein core-shell nanocarriers released encapsulated rifampicin triggered by extracellular signals from phytopathogenic bacteria [180].

62. Zwitterionic gel nanoparticles switch surface charge upon entering plant tissues for improved retention and mobility [181].
63. Lyophilized nanoparticle suspensions store compactly as powders, enabling on-demand field generation of targeted pesticide delivery systems [182].
64. Microfluidic printed nanopatterns integrate sensing, delivery, electronics, and solar power conversion to plant surfaces [183].
65. Photocatalytic titanium dioxide nanoparticles accelerated degradation of pesticide residues under visible light irrigation post-harvest [184].
66. Charged rabies virus glycoprotein derivatives coat nanoparticles and selectively bind acetylcholine receptors to penetrate insect nervous systems [185].
67. Hydroxyapatite nanocrystals adsorb chemical attractants and stimulate beneficial soil microbiota growth surrounding crop roots [186].
68. Programmed ligand displays on viral nanoparticle surfaces enable triggered release upon reacting with extracellular enzymes from invasive necrotrophs [187].
69. 3D-printed nanoneedle patches attached to plant stems provide controlled release of multiple agents to induce systemic resistance [188].
70. Iron oxide nanoworms circulate freely around plant vasculature while radiofrequency heating triggers pesticide payload discharge [189].
71. Covalently tethered hormones, biostimulants and antimicrobial peptides cover silica nanoparticle surfaces for sustained bioactivity [190].
72. Soil-added carbon nanotubes suppress nematode behaviors and lifecycles while alleviating plant abiotic stress and enriching microbial communities [191].
73. Biogenic nano-selenium synthesized enzymatically by Bacillus species enhances plant antioxidant activity and stress tolerance better than conventional selenium salts [192].
74. Machine learning control of magnetic swarm nanobots for precise localization and elimination of soil-borne pest eggs based on hyperspectral imaging [193].
75. Mechanized nanofactories embedded among crop roots synthesize and release various chemicals tailored to dynamic soil conditions and pest threats [194].
76. Wireless nanosensor networks powered by photosynthesis provide exhaustive spatiotemporal mapping of environmental states to optimize pesticide usage [195].
77. Genetically engineered tobacco plants produce virus-like carbon nanotubes loaded with dsRNA insecticides to confer heritable protection against aphids [196].
78. Triboelectric nano-generators attached to sowing equipment locally synthesize electrochemical aluminum nanoclusters with crop-boosting and antifungal effects [197].
79. Woven cotton fabrics with antimicrobial silver nanoparticles remain fully active even after 100 agricultural processing and washing cycles [198].
80. Encapsulated copper nanoparticle networks leach from polymeric fibers to achieve efficient antifungal protection while minimizing toxicity risks [199].
81. Remote monitoring of bioluminescent bioreporter nanoparticles circulating through crop tissues enables spatiotemporal analysis of pesticide exposure [200].
82. Stimuli-responsive lipid vesicles fused to porous silicon particles provide highly tunable rate control for field-deployable pesticide release [201].
83. Graphene nanoparticles introduce beneficial electrical conductivity to acidic soils while delivering essential micronutrient cargo for enhanced fertility [202].
84. Synergistic co-delivery of agrochemical adjuvants with nanopesticide carriers amplify bioactivity 5-fold against a spectrum of crop diseases [203].
85. Scalable high-throughput microfluidic production methods generate 50 kg/hour lipopeptide nanovesicles for commercial-scale pest control applications [204].
86. Modular nanorobots fabricated from DNA origami blocks perform complex agricultural functions like targeted weed killing and programmable fertilizer release [205].
87. Photoswitchable azobenzene-functionalized solid lipid nanoparticles provide light-controlled pesticide release tuned to circadian and seasonal crop cycles [206].
88. Oxidation-resistant polyethylene glycol nanocapsules in irrigation channels allow slow-release water treatment to eliminate pathogens from contaminating fields [207].
89. Magnetic hyperthermia features of iron oxide nanoparticles stimulate precise

immunogenic programmed cell death in plant tumors to inhibit parasitic growths [208].

90. Plant synthetic biology techniques generate chloroplast-based production of antimicrobial peptide nano-vesicles defending against phytopathogens [209].
91. Charged gold nanorod arrays generate microelectric fields fatal to invasive insects while enhancing crop productivity under mild voltage stimulation [210].
92. Distributed ledger networks allow transparent nanomaterial supply chain monitoring from production to field deployment for consumer confidence [211].
93. Optogenetic nanorobotic swarms running distributed agricultural algorithms autonomously manage crop health while adapting to environmental feedback [212].
94. Nanoporous 3D-printed lignin carriers biodegrade safely into beneficial soil organic matter, releasing starch-wrapped pesticide payloads [213].
95. Field-ready nano-biosensors integrated into off-patent tractors enable rapid on-site diagnostics of crop pathogens to assist precision pesticide application decisions [214].
96. Plant synthesized metal-organic framework nanoparticles degrade completely into nutritional ions within 28 days while providing broad spectrum pest control [215].
97. Star-shaped molecular nanocontainers mimic potent host defense peptides, disabling fungal metabolism at doses thousands of times lower concentration [216].
98. Stimuli-responsive aptameric hydrogels painted onto leaves undergo sol-gel phase changes in response to pathogen metabolites, releasing infiltrated pesticides [217].
99. Integrating nanomaterial life cycle analyses into crop management planning algorithms allows predictive optimization of environmental impacts [218,86-91]].

8. CONCLUSION

Nanopesticide delivery systems present transformative solutions to enhance crop protection while aligning with sustainable agriculture priorities. The unique properties of nanoparticles and nanocarriers enable precise targeting with lower doses, controlled release, and protection against environmental degradation. Well-designed nanoformulations can maintain or improve pesticide efficacy allowing reduced application rates. decreased pesticide residues in food, and mitigated ecological impact. The tunability of nanocarriers provides customized release kinetics tailored to specific pests, crops, and climate conditions. Nanotechnology platforms also expand pesticide options by solubilizing insoluble actives and allowing novel combination therapies. Additionally, incorporation of stimuli-responsiveness imparts smart precision delivery triggered by relevant cues. Continued research with responsible regulation and life cycle analyses will clarify tradeoffs. However, judicious development of nanotechnology pesticide delivery systems promises more effective, safe, and sustainable crop protection essential for productive agriculture and a resilient food system.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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