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Nanopesticides in the Era of Sustainable Agriculture: Comparative Insights with Conventional Pesticides, Cost-Benefit Analysis, and Future Perspectives

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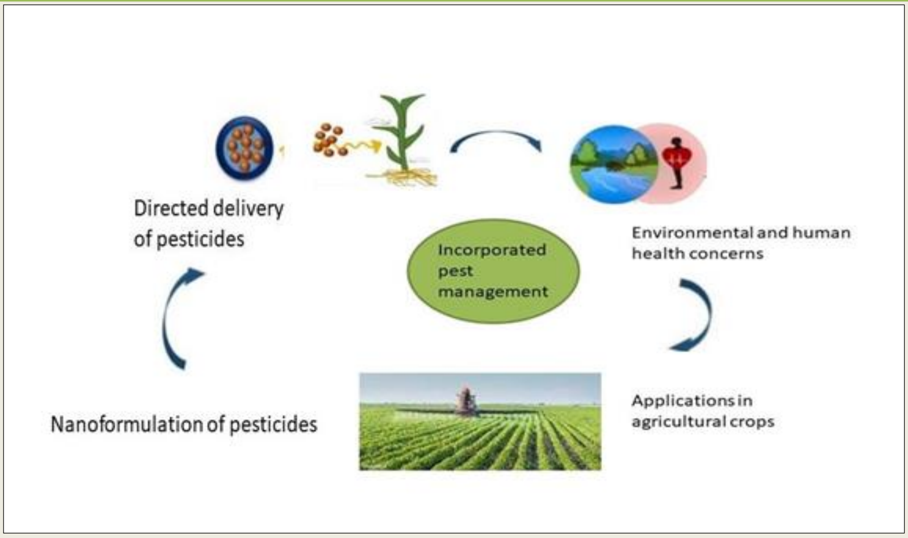
Abstract **Review Article**



Graphical Abstract

The main purposes of this study are to investigate the potential of nanotechnology in revolutionizing pest management through the development of nanopesticides and to address the environmental and health concerns associated with traditional agrochemicals and nanopesticides. This study utilizes a review methodology to examine the current state of nanotechnology applications in pest management, focusing on the formulation, advantages, and challenges of nanopesticides. It also explores the adverse environmental and medical effects resulting from the use of conventional pesticides and the potential benefits of nanostructures in pesticide delivery. The results highlight the potential of nanotechnology platforms in enhancing the effectiveness of pesticides through improved bioavailability and targeted delivery mechanisms. Nanopesticides offer advantages over traditional agrochemicals by minimizing environmental damage and health risks associated with leaching, evaporation, and unintended exposure. However, the rapid development of synthetic nanoparticles poses new challenges related to environmental pollution and waste management. Nanotechnology presents promising opportunities for sustainable pest management by addressing the limitations of

traditional agrochemicals. The formulation of nanoscale pesticides offers enhanced efficacy and reduced environmental impact. However, careful consideration of the potential adverse effects and responsible waste management strategies are necessary to ensure the safe and sustainable implementation of nanopesticides in agriculture.
Keywords: Nanocarriers, Pesticide Agents, Metal Nanopesticides, Pesticides Nanoformulation, Environmental Risks, Health Concerns.

Highlights:

- Conventional pesticides towards Nanopesticides
- Nanoformulation of pesticides
- Nanopesticides's environmental risks and benefits
- Applications, challenges and future perspectives of nanopesticides

1 INTRODUCTION

Food shortages and crop yield loss are the results of the world's growing population and the application of traditional pesticides (Zainab, 2024). In addition to being in a highly developed stage of research and development, nanopesticides have begun to hit the market (Kah, 2021).

There are continuing efforts to achieve innovative ways to enhance food production, as the world population is projected to grow about 48% via 2050 (Henning, 2017). Because of dwindling agricultural regions, increasing urban populations, and rising food demand, the majority of crop types are currently farmed on a vast scale in monocultures that cannot be sustained without the use of agricultural products. Pesticides, fertilizers, growth stimulants, and other agrochemicals are estimated to be worth $266 billion via 2021, with 4.5% annual growth rate (Market, 2018). Nanoscience and nanotechnology play an effective and precise role in increasing agricultural yields and supporting management choices through the use of high-tech sensor and analytic systems. Nanotechnology is applied in the modern agriculture industry for pest management and diagnostics (Ali *et al.*, 2021). Understanding nanoscience as well as nanotechnology allows us to improve pesticide effectiveness, minimize pesticide requirements, and reduce active ingredient losses. and also enhance the tolerance ability of plants against various stresses and hence improve the production of crops (El-Moneim *et al.*, 2021). In agriculture, pests like diseases, dangerous insects, or parasitic plants pose a serious concern because it threatens the stability and reliability of food production, thereby endangering food security. Pesticides are quite important. in safeguarding soil health, eradicating harmful pests and insects, and upholding the security of our food supply (Iavicoli *et al.*, 2017; Rodríguez and León, 2020).

Insecticides, fungicides, herbicides, and rodenticides are just a few of the pesticides used to protect crops against pests and increase crop output. Insects pose a significant threat to human health and agriculture, but traditional insecticides are highly hazardous to humans, necessitating the development of sophisticated pesticides.

The consequences they have on humans, birds, honeybees, and other creatures, however, can be very negative.

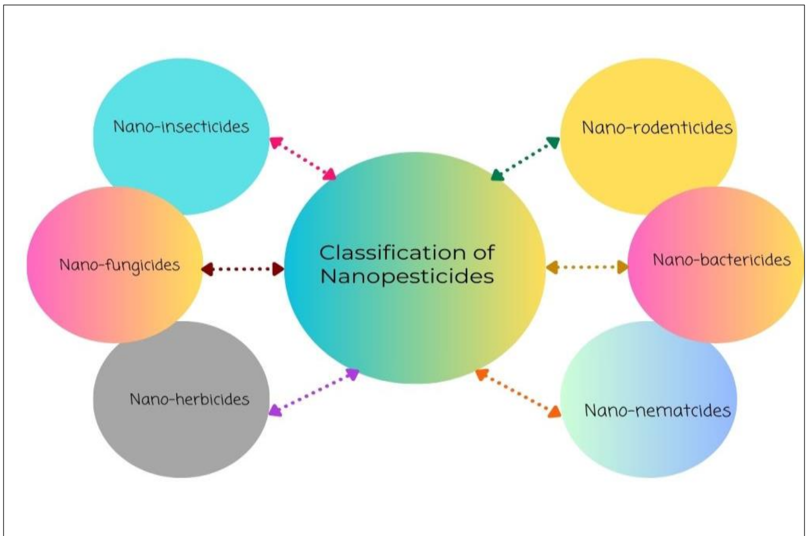


Fig. 1: Classification of Nanopesticides

Furthermore uncontrolled application of these pesticides boosts pesticide deposition in agricultural and animal products, aquatic creatures, and disease resistance, reduces nitrogen fixation, and hinders the nitrate cycle (Chaud *et al.*, 2021). As a result, during the last decade, the hunt for novel biocompatible as well as biodegradable agrochemicals utilising responsive materials has expanded.Pesticides are mostly created by using nanotechnology to minimize the precarious effects of pesticides and form their application to plants. However, The word "nanopesticide" is most commonly associated with controlled release methods that contain active chemicals that are encased at the nanoscale in (typically biodegradable) nanocarriers (Singh *et al.*, 2020). Scientists and farmers alike are becoming more and more interested in using nanopesticides. Nanoformulations have been proven in studies to minimise drift and volatile wastes after application. Several plant-derived products (PDP)-based biopesticides have been synthesised as nano-formulations (Deka *et al.*, 2022). This will reduce chemical loads and treatment costs while increasing crop yield (Das and Brar, 2018). PDP nanopesticides have not yet been compared to other market products. Encapsulation and other approaches may improve PDP selectivity and bioefficacy, while reducing environmental and human risks.

As a result, researchers and extension agents are increasingly interested in using nanopesticides, which are composed of organic and inorganic ingredients including nano-sized particles of an active pesticide ingredient (AI) or other tiny designed structures with pesticide capabilities. Because nanoformulations can either increase or decrease the mobility of AI, field bioefcacy and the potential impact of nanopesticides on ecological systems may differ from laboratory results (Kah *et al.*, 2018). Nanomaterials may be employed as effective pesticide delivery agents, such as insecticides, herbicides, fungicides, and antimicrobials, and can help us advance towards self-sufficiency and environmentally friendly agricultural goods for crop protection and management (Raj *et al.*, 2021). This new generation of pesticides, by controlled release and targeted delivery, can enhance the accessibility of the active components and hence be effective in contrast to their predecessors (Mustafa *et al.*, 2018).

The primary benefits of using nanopesticides h ave been reported as being the decrease in concentration and frequency of treatment in the field, the avoidance o f high application rattes, thereduction of waste, and the reduction of hazards of exposure to nontarget organisms (Pascoli *et al.*, 2018; Takeshita *et al.*, 2021). Technologies that use solid lipid nanocarriers (SLNs) and biodegradable polymer poly-caprolactone (PCL) as nanocarrier systems to load atrazine have been created and evaluated. The efficiency of nanoencapsulated atrazine, frequently referred to as nanoatrazine, against herbicides has been tested in the field using the species of interest Brassica juncea (Takeshita *et al.*, 2021). It is expected that this study would address the knowledge gap and assist to keep up with the most recent advancements in this sector of RDI, whereby holistic pest control is used in conjunction using green technology, notably for protection of plants.This review attempts to consolidate and update information on the latest developments in agrochemicals, current trends, and pesticide nanoformulation.

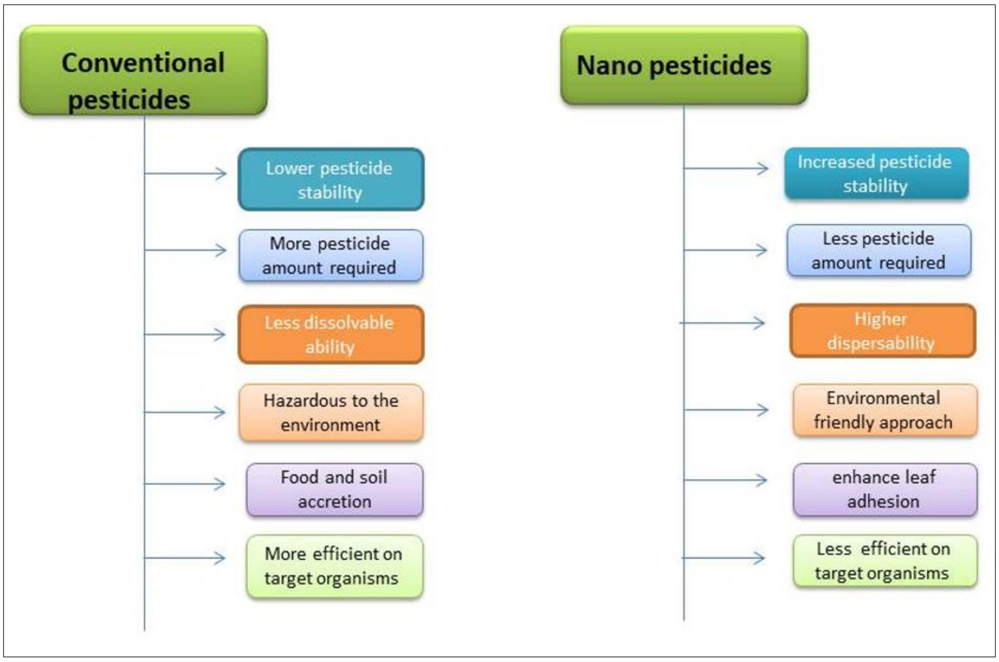


Fig. 1.1: Comparision of conventional pesticdes and nano pesticides

Inefficient pesticide use leads to ecological and environmental consequences. Pathogen and insect resistance, non-point contaminants, eutrophication of water sources, soil deterioration, food chain bioaccumulation, biodiversity loss, emulsifiable concentrate (EC) and wettable powder (WP) are the two most common conventional pesticide formulations. WP is a pesticide formulation that combines active ingredients (AIs), inactive fillers, and preservatives. The inorganic additives in WP can readily flow off into the environment, preventing full discharge of loaded AIs. Furthermore, the leftover insecticides are difficult to breakdown. Pesticide are submerged in a solvent, mixed with an emulsifier, then diluted in water to create a stable emulsion. Pesticide spraying releases organic solvents and hazardous substances into the environment, causing major pollution in aquatic and soil systems.

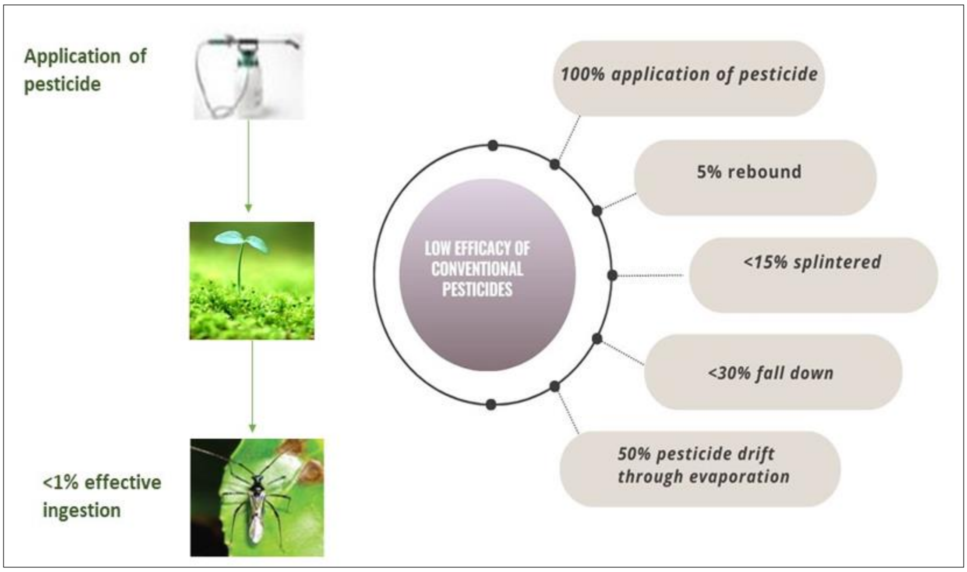


Fig. 1.2: Low efficacy of conventional pesticides

1.3 Nanopesticides: Concepts and Perspectives

Pesticides typically consist of an active component (AI) designed to deter, eradicate, deter, or control pests, or serve as a plant growth regulator, leaf remover, drying agent, or nitrogen stabilizer Ingredients that are inert (II), yet are essential for item functionality and accessibility, are combined with the AI. Many databases, including IUPAC, EU, and others, have provided the fundamental information and additional details about it. The fundamentals and other details of AI for pesticides have been described in numerous databases, including IUPAC, EU, and others.Furthermore, a study of ecotoxicological as well as regulatory elements of nanopesticide environmental sustainability may be found elsewhere (Grillo *et al.*, 2021; Zobir *et al.*, 2021).

Nanopesticides refer to pesticides that have been incorporated into nanomaterials for use in agriculture. These insecticides can be connected to composite substrates, encased in a matrix, or embedded in nanocarriers that responsive to environmental stimulus. Nanoscale particles, each having their own distinct forms and characteristics, would improve pesticide efficiency when packaged in novel carriers comprised of different substances (Agostini *et al.*, 2012). Nanopesticide formulations have the potential to revolutionise agricultural disease, weed, and insect management by enhancing water solubility, bioavailability, and preserving agrochemicals from environmental degradation (Yadav *et al.*, 2020).

Yet, the characteristics of nanomaterials are also on the border of cytotoxicity and genetic toxicity. The uncontrolled and illogical applications of pesticides disrupt the ecosystem's equilibrium and jeopardizes health of each person. Pesticide exposure makes children more susceptible to lasting cell and organ destruction. Concerns are raised by the centra and periphery neurotoxicity, as well as the influence on the loss of blood coagulation capacity (Kuhlbusch *et al.*, 2018). Certainly, conducting a comprehensive evaluation of the advantages and disadvantages that impact the efficacy and nanopesticides toxicity is critical for assuring the safe and sustainable progression of nanoparticle usage in agriculture, which has already been approved. The influence of these preparations on the actions of nanopesticides to diverse settings, ecosystems, worker health, consumer health, and all sectors that utilize the supply chain associated with agriculture remains unknown (Huang *et al.*, 2018). Nevertheless, it is well recognized that nano formulations play an important role in avoiding active ingredient degradation, improving water solubility equilibrium, and boosting the biochemical accessibility of such active ingredients. This is especially crucial for preventing extensive insect infestations, minimizing plant damage, and limiting economic losses by protecting agricultural output quality and quantity (Syafrudin *et al.*, 2021).

1.4 Utilizing Nanopesticides

Nanopesticides are made up of very small adjuvant pesticide particles or another small, purpose-built structures having useful pesticide capabilities. A product known as a nanopesticides uses nanoscale techniques, such as the usage of materials with a minimum of one size dimension between 1 and 100 nm) to enhance performance or efficacy. Products like these, which are at various stages of development and can be utilized to increase the increase the effectiveness of the active components in existing pesticides either both, or their pollution control characteristics. Nanopesticides have already been utilized to combat several cattle pests. In terms of pesticide use, nanopesticides are a relatively new technological development that offer a number of benefits, such as long-lasting effectiveness and low amounts of potentially harmful active components. emulsions (such nano emulsions), nano capsules (like those with polymers), and goods containing pristine-engineered materials.

Metal, metal oxide, and nano clay nanoparticles, for example, are all suggested to be formulation types. Determined through testing of these combo nanopesticides whether or not the existence in terms of nano formulation has any potential modifications in relation to the regularly used active components employed acaricides. The evaluation looks at impact's estimation. Placing nanoparticles on unintended organisms can facilitate research directions for nanopesticides. Biochemical BCF to assess potential risks associated with high classification of chemicals and taxonomic groups (Kah and Hofmann, 2014).

2 METAL NANOPESTICIDES

2.1 Gold Nanoparticles

Gold nanoparticles are commonly utilized for medical purposes, such as diagnosis and medicine delivery. Au nanoparticles made from plant extracts have gained popularity due to their strong antibacterial properties and ease of salt reduction. The majority of research reported the Au nanoparticles can be made from plant extracts and chemicals utilizing green synthetic approaches, such as production from jasmine nervosum (Lallawmawma *et al.*, 2015), Sphaeranthus indicus, Citrus limon due to their insecticidal activity. Au nanoparticles effectively limit the amount of larvae of the mosquito the Aedes aegypti, a major carrier of dengue disease and Zika virus globally. The effectiveness of green synthesized Au nanoparticles towards mosquito vector management has been studied more extensively on Aedes aegypti than other species. Au nanoparticles produced from Chloroxylon swietenia extract of leaves had a (LC50) value corresponding to 0.340 ppm (mg/L) towards Aedes aegypti (Balasubramani *et al.*, 2015).

Herbs utilized in mythology and traditional medicine have been utilized as reducing substances in the synthesis of Au nanoparticles. These botanicals contain phytochemicals that are innately poisonous to larvae, resulting in significant insecticidal action. Chrysosporium tropicum, a keratinophilic entomopathogenic mold, produces macromolecules that effectively regulate larvae.

Au nanoparticles derived from fungi were found to be highly effective towards Aedes aegypti. Chrysosporium tropicum's Au nanoparticles were evaluated as a pesticide against Aedes aegypti I instar larvae at a dosage level of 0.77 ppm (mg/L), resulting in a full mortality rate after a period of 24 hours (Namita Soni and Soam Prakash, 2012). Nanoparticles have been reported to serve as effective pesticides due to their ability to penetrate the cuticle directly. Dispensable consumption to kill insects. Zein, a natural, sustainable, biodegradable, and cost-effective biopolymer, can operate as a reducing agent in the synthesis of Au nanoparticles. The tested insects exhibited histological abnormalities, including abdomen disintegration and hair loss. Stereomicroscopic visualization revealed hair loss in several locations of Aedes aegypti, including upper, lower, antenna head, lateral, and caudal hairs (Suganya *et al.*, 2017). Au nanoparticles are now effective against insects at all stages, including larvae, pupae, and adults, thanks to advancements in research.Green Au nanoparticles function exceptionally well as insecticides, as evidenced by increased predation efficiency among natural enemies. Future research will focus on understanding the mechanism of pest-killing effects, as well as potential risks to the environment and health. The insecticidal effect of Au nanoparticles is attributed to their stability, however it is unclear if this is due to the raw materials or specific nanoscale features (Li *et al.*, 2023).

2.2 Copper Nanoparticles

Chemical production of nanoparticles involves a high-cost process that is deemed hazardous and has limited productivity. As a result, biological techniques for synthesizing from plants or microorganisms have potential applications since they are free of charge, safe, fast, and environmentally acceptable (Thakur *et al.*, 2018). Pseudomonas stutzeri is capable of producing cubical CuNPs from 50 to 150 nm by electroplating wastewater, however it cannot create spherical CuNPs within size ranges of 8 to 15 nm (Varshney *et al.*, 2010). Copper nanoparticle production has gained attention for its potential uses in biology and nanomedicine. Copper nanoparticles and complexes are currently utilized as antimicrobial, antiviral, and preventing fouling agents (Klaine *et al.*, 2008). Cu nanoparticles of Metarhizium robertsii were found to be highly effective in regulating pests including the mosquito-borne Aedes aegypti, cultivated quinquefasciatus, and the Anopheles stephensi, making them a promising new source of pest control. Cu nanoparticles produced via the polyol method showed larvicidal activity against the IV instar caterpillars of C. quinquefasciatus and the Anopheles stephensi with LC50 values 1.01 and 0.95 mg/L (Ramyadevi *et al.*, 2011).

Previous research has mostly focused on the remarkable mosquitocidal effectiveness of Cu nanoparticles. More research is needed to accurately determine pesticidal effects. In addition, the research should consider human and environmental risks, as well as their potential harm to nontarget creatures.

2.3 Iron Nanoparticles

One of the metals that is utilized in daily life the most is iron (Fe). Fe nanoparticle production and application have been thoroughly examined recently. However, Fe nanoparticles as a substitute for traditional pesticides are still in the early stages of development. In spite of the insufficient.Fe nanoparticles' prospective pesticidal qualities are highlighted by the data and study that are currently accessible. The extract taken from the evergreen tree, Ficus natalensis, via Fe nanoparticles on Culex quinquefasciatus, showed LC50 values ranging from 20.9 to 43.7ppm (mg/L) in larvicidal and pupicidal assays. In particular, guppies' predation rates on Culex quinquefasciatus larvae were concurrently increased, which might be attributed to a notable decrease in the larvae's motility following the application of Fe nanoparticles. Notably, the actual utilization of nanopesticides inside the external agricultural environment is contingent upon the completion of risk assessments related to public health and the environment. Their potentially harmful effects on aquatic organisms that are not targets were also established based on this premise. As a result, after more than a week of exposure to Fe and iron oxide nanoparticles, nontarget guppyfish Poecilia reticulata subjects showed no discernible negative effects (Murugan *et al.*, 2018).

The management of agricultural pests is a serious concern on a global scale, and safe and effective pest control techniques are desperately needed. As a result, plant-derived nanopesticides are remarkably useful insecticides. Our findings unequivocally demonstrate that FeNPs generated from T. foenum-graecum extract of leaves effectively inhibit T. absoluta. FeNPs exhibits strong insecticidal efficacy against T. absoluta pests even at very low doses. As a result, we advise choosing nano formulation-based insecticides, which are more efficient at controlling pests while also lowering environmental pollution and developing resistance to continued use of conventional pesticides (Ramkumar *et al.*, 2021).

2.4 Additional Metal Nanoparticles

Apart from the widely utilized nanomaterials stated before, various additional metal nanoparticles were also discovered for their potential to eradicate mosquitoes. Cobalt nanoparticles were produced by Bacillus thuringiensis. shown remarkable larvicidal efficacy against and Anopheles subpictus and Aedes aegypt with LC50 values of 3.59 and 2.87mg/L, respectively (Marimuthu *et al.*, 2013). Bimetallic nanoparticles' mosquitocidal qualities were also identified. Citrus lemon leaf extract was used to create bimetallic gold and palladium nanoparticles, which demonstrated larvicidal efficacy against Aedes aegypti and Anopheles stephensi during the whole instar phase (Minal and Prakash, 2020). According to all of the above mentioned facts, using metal nanoparticles in accordance with green biofabrication for pest management is potentially useful.

3. Nanocarriers for Delivering Pesticide Agents at the Nanoscale

Traditional pesticide distribution systems are crucial for agricultural applications, but there is a need to enhance their efficiency and address issues such as spray drift. A promising solution to tackle these challenges is the judicious utilization of controlled delivery systems. Controlled delivery entails the exact release of pesticide components in suitable proportions, customised to the crop's individual needs, while eliminating the need for excessive agrochemical use to battle target pests (Tsuji, 2001). In the pursuit of global precision agricultural improvement (Ma, 2019). Nanotechnology has received a lot of attention recently for its role in adapting and modernising traditional pesticide application technologies. Nanotechnology is a scientific and technical subject that includes the creation, study, control, and use of materials at the nanoscale, with structures measuring 100 nanometers or less, known as nanomaterials. This breakthrough intends to change the way agrochemicals are applied to the environment.

Nanostructured systems include nanoparticles such as nanocapsules, nanospheres, nanocrystals, nanocomposites, nanotubes, and nanoneedles, as well as micro/nanoemulsions, which are compounds of fuller and comparable systems. These systems provide a fertile ground for agricultural research (Ghormade *et al.*, 2011). Nanostructured systems serve as carriers for chemical compounds used in farming, facilitating the gradual and precise delivery of these substances. This controlled release is made possible by their small size, high surface-to-volume ratio, core-shell diffusion system packaging of active agents, and distinctive optical properties. Numerous scientific studies have demonstrated shows the utilisation of nanostructures with active chemicals as controlled release devices for these medications is extremely successful.

Table 1: Comparison of different pesticide agents

Nanocarrier / (average size)	**Pesticide agent**	**Preparation Method**	**Purpose**	**Applications**	**References**
Hybridised organic-inorganic molecules	2,4 dichlorophenoxy acetate	self-assembling	Reglatory release pesticide /herbicidal activity	The resultant substance (ZAD) was then employed to research the release property of 24D into distilled water, chloride, and carbonate-containing aqueous solutions.	(bin Hussein *et al.*, 2005)
Chitosan	Paraquat	Alginat pre-gelation followed by a complexation of alginate and chitosan	Insecticidal activity	increased duration of the chemical's impact on certain targets while lowering ecological toxicity issues	(dos Santos Silva *et al.*, 2011)
Poloxamer	Tropicamide	Encapsulation	Less toxic and non-irritant	On Vero cell lines, the egg test of hen, chorioallantoic barrier, and resazurin assay demonstrated great ocular tolerance. and biocompatibility for the tropicamide-loaded TSX nanoaggregates formulation.	(Dilbaghi *et al.*, 2013)
Tripolyphos phate	Chitosan, $CUSO_4$	Cross linking	Antifungal activity	Used to kill fungus on larger scale	(Saharan *et al.*, 2013)
Carboxy methyl chitosan	Methomyl	Encapsulati on	Pesticide release property	Regulate release for an extended amount of time	(Kutscher *et al.*, 2015)
Carboxymethyl-ß- Cyclodextrin-Felon, magnetic nanoparticles-Diuron (CM-B-CD-MNPs-Diuron),	Diuron	Supramolecular Chemistry (host-guest method)	To a certain extent, the presence of moderate organic matter CM-B-CD-MNPs-Diuron in soil stimulates the growth of actinobacteria.	This work demonstrated that CM-B-CD- MNPs-Diuron has less toxic the sluggish emission of diuron by CM-B-CD-MNPs into the soil specimen may explain why diuron has more impact on soil than diuron.	(Liu *et al.*, 2014)
Micelles of 2-nitrobenzylcarboxymethyl-chitosan succinate (140 nm)	Diuron	Side chain graft and conjugation technique	Photo-controlled release of pesticides	Higher rate of photo-controlled release (96.8%) with sun radiation stimulus lasting up to 8 hours (at pH 7).	(Ye *et al.*, 2015)

N-doped TiO_2	Plantago major seeds extract size distribution 50+-1.8nm	Mean particle size distribution of nano capsules (380nm)	Nanoparticles of trimethylammonium and mesoporous silica / (423 nm)	Nanoparticles of gum arabic (226 nm)	BzLCN (40nm)	Ag-doped hollow TiO2 nanoparticles (50 nm)	Silica
Enzyme alpha amylaze (Capping agent)	benzene dicarboxylic acid (23.49%). dodecane (9.17%), 1-ethynylcyclopentanol (7.36%), hep- tadecane (6.47%) and cyclohexanol (4.56%)	Eucalyptus extract (1,8-cinehole)	2,4 dichlorophenoxy acetic acid	Linalool and carvacrol	X-Cyhalothrin	……	Pyridoxine, Piracetam
Plasma-assisted method	Encapsulation	Encapsulation	Nanosilica graft post and Sol-gel	Ionic gelation	Emulsion	Alcoholic dispersion chemical reaction	Suspension
Anti-bacterial and anti-fungal activity	Insecticidal activity	Insecticidal activity	Using herbicides on dicot plants	insecticide treatment for Tetranychus urticae and Helicoverpa armigera	characteristic of pesticide release	Fungicidal activity against Venturia inaequalis and Fusarium solani	Abounding brain tissue
Numerous bacteria, including TiO2 inhibits Aeromonas bacteria hydrophilic, S. aureus, Escherichia coli, Proteus mirabilis, & the bacterium Pseudomonas	Plantago major seed extracts in nano capsules exhibit positive effects on the pest and is a viable alternative to synthetic insecticides.	The insect Myzus persicae is harmed by nano-encapsulated eucalyptus extract, which is a potent substitute for synthetic insecticides.	Pesticides were loaded due to electrostatic interactions, which also controlled compound release by reducing leaching in the soil.	Inhanced mortality rate	--------------	Excellent Fungicidal action in the presence of natural lighting.	Increase the medications' capacity to pass across the barrier between the blood and the brain. after entering the circulatory system.
(Pho *et al.*, 2020)	(Khoshraftar *et al.*, 2020)	(Khoshraftar *et al.*, 2019)	(Cao *et al.*, 2017)	(Campos *et al.*, 2018)	(Zhou *et al.*, 2018)	(Boxi *et al.*, 2016)	(Jampilek *et al.*, 2015)

CuO-FLS (nano-needles 100–200 nm) Chitosan	Star polymer based cyantranilipro le CNAP (808nm)	Chitosan based rotenone nanoparticles	Mean particle size of BNPs (100nm)	N-doped CDs
Copper acetate monohydrate (Cu $(CH_3COO)_2.H_2O$) Pyrrol	Anthranilic diamide	Rotenone	Buprofezin	….
Direct precipitation method Sol gel method Nanosuspe nsion	Oral feeding method	Emulsion, Crosslinking	Anodic aluminum oxide template assisted method	Plasma Technology Cross linling
Insecticidal activity	Insects control	Insecticidal activity	Insecticidal activity	Anti-bacterial and anti-fungal activity
For the management of the Autumn Armyworm (Spodoptera Frugiperda), CUO with flower-like (CuO-FLS) and rod-like (CuO-RLS) structures is used as an alternative insecticide. Direct usage of CHL chitosan nanopesticides on maize roots reduces environmental pollution. Pesticide drift causes less damage to nontarget organisms and slows the progress of insect resistance. This study proposes novel approaches to the production of better photostable, sticky, rainfall erosion-resistant, and ecological nanocarrier insecticide. The solution we tested not only fits pest management requirements, but also improves pesticide utilisation	improves natural enemies' selective toxicity	Red fire ant aggression was markedly reduced by the CS/ CMCS/Rot-NPs created for this study, and the amount of red fire ant venom alkaloid and their habitat was also decreased.	The preparation of hydrophobic nanodrugs using the AAO template method is flexible and practical, and it set the stage for investigating the characteristics of drug particles of various sizes.	In terms of affordability, non-toxicity, and photoelectricity, CDs outperform other conventional materials. Additionally, CDs-based photocatalysts are soluble in water and not dangerous to humans. It functions as a biosensor for spotting harmful illnesses in agriculture.
(Ayoub *et al.*, 2022) (Zheng *et al.*, 2023)	(Yan *et al.*, 2022)	(Zheng *et al.*, 2022)	(Wang *et al.*, 2021)	(Pho *et al.*, 2020)

3.1 The Formulation of Nanoscale Pesticides

Knowing the precise chemical makeup of the entire formulation, not just the active ingredient, is crucial for evaluating the safety of nanopesticides. As previously indicated, there are three primary techniques to create or synthesise active chemicals for nanopesticides at the nanoscale:

1. When a nanomaterial is an active component.
2. While it is not a nanomaterial but is packed in nanoscale carrier (such as a hollow/porous component, shell, or capsule),
3. When both categories are combined in only one system (Pestovsky and Martínez-Antonio, 2017). Since these will be addressed in regulating danger assessments for non-specific qualities, it is crucial to highlight that safety concerns will be equally significant under both circumstances (Committee *et al.*, 2018).

Examples of the first kind of nanopesticides may be anticipated as a kind of chemically active ingredient(s) which are either produced nanomaterials such as nanoparticles of metal (such as silver & copper) and synthetic nanomaterials (Guilger-Casagrande *et al.*, 2019) or nanoscale metal oxides (such as titanium dioxide, manganese dioxide, silicone dioxide, and zinc oxide) (Elmer *et al.*, 2018; Lakshmeesha *et al.*, 2020; Shukla *et al.*, 2020). However, it would seem from the present R&D trends in this field that the majority of nanopesticides in development fall under the second category. Basic emulsions of oil in water, liposomes, solid fatty acid nanoparticles, and nano-encapsulates made of either synthetic or natural polymers or encapsulated within a void or permeable nanoparticle including carbon nanotubes , are examples of such formulations of pesticides at nanoscale (Vega-Vásquez *et al.*, 2020; Grillo *et al.*, 2021). This makes sense given that nano-scale formulation is a practical advancement over the already employed micro-scale formulation for pesticides. Two methods can be used to create nano-pesticides: loading pesticides onto nano-carriers in delivery systems, or directly converting the product into nanoparticles (nanosized pesticides). Pesticides are loaded into nanocarrier systems by encapsulating them within the nanoparticulate polymer layer and then absorbed onto the surface of the nanoparticle, ligand-attached adhesion to the nanoparticle core, or entrapment inside the polymeric matrix. It involved top-down techniques like sonication, high-pressure homogenizing, and grinding to reduce size. The bottom-up methods, on the other hand, include emulsion, complex coacervation, liquid dispersion, fluid displacement, and interface polymerization (Gao *et al.*, 2011).

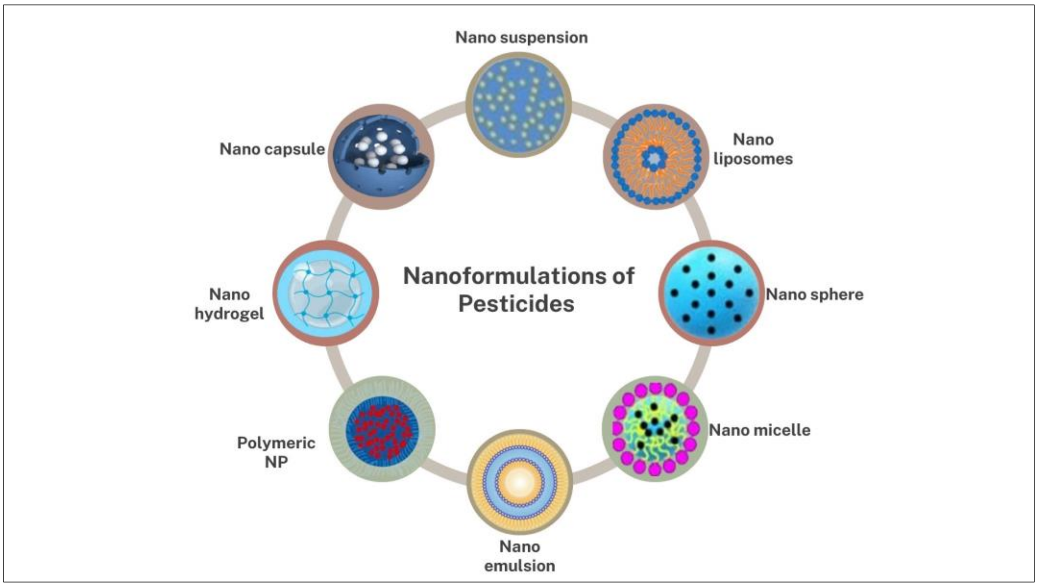
Additionally, several current pesticide micro-emulsions have been discovered to contain nanoscale droplets (Kah *et al.*, 2013). The nanopesticides nano-encapsulation techniques presented are analogous to those being researched for other chemicals used in foods, pharmaceuticals, and cosmetics. Polymers used in nano-encapsulation include alginate, the carrageenan cellulose gum, chitosan, and modified starch, as well as proteins (chicken albumin from eggs, the zein, casein, an amino -lactalbumin, -lactoglobulin, the protein collagen, and gelatin) (Pestovsky and Martínez-Antonio, 2017). Additionally, more recently, Nanopesticides with improved biodegradability and reduced prices have been created using different biopolymers, including cellulose, lignin, chitins, and others (Elabasy *et al.*, 2020; Hao *et al.*, 2020). In addition, research have documented the development of sluggish- or fast controlled-release products in order to provide tailored effectiveness lifespan for the outdoor application of Nanopesticides (Zhou *et al.*, 2018; Camara *et al.*, 2019).

There is a great deal of promise for enhancing formulation characteristics such water dispersion, chemical stability, targeted adhesion, permeability, and controlled release with nanoemulsions, nanomicelles, nanospheres, nanocapsules and nanosuspensions (Elsharkawy). Pesticide AIs are encapsulated in the inner core of nanocapsules, which are structural vesicular with a core-shell structure. Biodegradable polymeric materials, such as polyε-caprolactone (PCL), and polyglycolic acid, polyethylene glycol (PEG), , chitosan, and others typically make up the shell. . Because the polymeric shell breaks down gradually in the environment, it increases the chemical stability of molecules that are sensitive to the environment (such as those that deteriorate due to UV light or soil erosion). Additionally, by modifying the membrane polymeric leaf's affinity, nanocapsules can improve the efficiency of targeting delivery by enhancing the behaviors of droplet spreading, absorption, and wetting on leaves (Campos *et al.*, 2015).

Pesticides are uniformly dispersed inside solid spherical vesicular systems called nanospheres by means of adsorption or trapping inside the nano-matrix. The nanospheres are made up of either inorganic mesoporous materials or organic polymer materials, like porous hollow silica, non-metal oxides, and activated carbon. Due to their high drug-loading capacity, excellent biocompatibility, and slow delivery pattern, nanospheres have shown considerable promise in the treatment of soil infections and pests (He *et al.*, 2015).

Nanotechnology includes nanosuspensions. Micron-sized colloidal suspension of medicinal active component particles in a fluid state regulated by surfactants is what makes up nanosuspensions. A novel and affordable method for addressing low bioavailability associated with hydrophobic drug delivery—including those with solubility in aqueous media—is nanosuspension technology. Nanosuspensions are crucial vehicles for creating cutting-edge medication combinations. Nanosuspensions are used in a variety of dosage forms, including specific drug delivery systems like mucoadhesive hydrogel. Nanosuspensions' distinct properties have made them suitable for usage in a variety of dosage formats, incorporating customized delivery systems like mucous adhesive hydrogels. Currently, attempts are being made to expand their applicability in location-specific delivery of drugs (Chandra *et al.*, 2013).

Nano emulsion nanoscale droplets (oil/water system) with diameters less than approximately 100 nm are what produce nanoemulsions (Anton and Vandamme, 2011). Even if there could not be any meaningful distinctions between nanoemulsions and microemulsions, the physical characteristics of microscale emulsions and nanoemulsions might differ significantly. A "low-energy" method of creating nanoemulsions is described, in which two liquid phases—one homogenous and composed of a hydrophilic surfactant and lipophilic phase, along with possibly a solvent, polymer, or drug are brought into contact with each other. Next, the oily phase's hydrophilic species quickly solubilize into the aqueous phase, causing the demixation of the fluid appeared in the shape of nanodroplets, which the amphiphiles quickly stabilized. Thus, it appears that this approach is the simplest and doesn't require any unique, high-energy gadgets (Gupta *et al.*, 2016). Pesticides can be perfectly encapsulated in nanomicelles, which are biologically efficient nano delivery devices. The external environment has the ability to generate changes in the chemical and physical characteristics of nanomicelles. For instance, using the cross-linked nanomicelle with hydrogen bonding as a basis. It was decided to build an environment-responsive controlled release mechanism. The pesticides released when the nanomicelle swelled, the hydrogen bonding broke, and the temperature and humidity increased.



3.2 Innovative-Nanoformulation Pesticides Encapsulated

Encapsulation is the process of confining a single naturally existing chemical in order for it to be dispersed into the surrounding environment under specified conditions over time or when outside factors cause the capsule sides to fracture or dissolve. The active component is put in a nanocapsule and chemically attached to or physically adsorbed to the matrix utilising a number of techniques. Pesticides are sometimes nanoencapsulated to prevent efficacy loss due to evaporation, degradation, and leaching, as well as enhanced activity due to greater interaction with an infectious agent such as weeds, insects, and other pests. The advantages and disadvantages of using pesticides with non-encapsulated environments should also be considered. Current research on new material systems that are stimuli-responsive at exposure to light, pH level, temperature, enzyme, and various other levels are currently revealed for agrochemicals broadening release, targeting delivery, reducing usage quantity, diminishing releasing and drift, and improving pesticide utilisation efficiency. This sits in line with agrochemical firms' present emphasis on growing the crop irrespective of the optimal circumstance (Chen *et al.*, 2018; Zhang *et al.*, 2019; Gao *et al.*, 2021; Xiao *et al.*, 2021).

Depot systems are terms used to describe innovative and controlled release formulations. This terminology implies that there is a temporal lag between the first application of encapsulated nanopesticides on the field and active ingredient releasing process. This differs from traditional formulations, which result in an instantaneous, abrupt release of AcI after administration to the crop. As a result, whether employing a depot-based system or an instant release formulation, the intended impact will be seen only when the lowest feasible concentration is accomplished (Ning *et al.*, 2017). A very high loading rate in a depot system provides controlled release over a lengthy period of time and reduces dosing frequency to every five months. The needed application quantities are many times of magnitude lower than in conventional formulations, and the action of the nanopesticides is extended (Bahadir *et al.*, 2012). Innovative nanotechnologies work to ensure a safe application of traditional pesticides while reducing their indiscriminate and abusive use. The most cutting-edge technological development for the secure application of pesticides and new strategies for supplying novel nanopesticides materials is currently for environmental stimuli-responsiveness, attached target nanoparticle compositions were developed.In order to deliver pesticides, sensitive polymer material has been used to create and materials with nanostructured matrix structures, including nanocapsules, nanospheres, & nanovesicle (Balaure *et al.*, 2017; Huang *et al.*, 2018; Zhang *et al.*, 2019).

Seltima submicron capsule was developed to mitigate the toxicity associated with pyraclostrobin. This innovation resulted in the creation of a regulated release mechanism that is sensitive to humidity. This system was intentionally designed to advantage of rice foliage and various other crops.while ensuring the protection of aquatic environments. A thermosensitive nanocapsule was developed using emulsion polymerization to efficiently release pyraclostrobin over a specific time period. This method, which used poly (N-isopropyl acrylamide-co-butyl methacrylate), not only improved pesticide stability but also extended its efficacy (Balaure *et al.*, 2017). A novel pesticide release mechanism that reacts to environmental signals can minimise early pesticide binding, reduce sulfidation reactions, and provide long-term pest control efficacy (Agostini *et al.*, 2012).

3.3 Encapsulation Based on Polymers

Polymers are one of the most popular nanomaterials used to cover active ingredients (AI). According to (Kumar *et al.*, 2017) the key advantages of these formulations are their low cost, biodegradability, and absence of hazardous byproducts. Polymers such as chitosan, polyethylene glycol, alginate, gelatin, and poly-caprolactone are widely used to encapsulate nanopesticides. This drug, contained in nano-dispensers, has been found to exert effects on disease vectors at 200 times lower AI concentrations than standard formulations (Meyer *et al.*, 2015). Because AI is used so infrequently, it is largely safe for both humans and the environment (Kumar *et al.*, 2019) to regulate the release of AI, the kind of polymeric nano formulation utilized in this synthesis—for example, microcapsule, microemulsion, etc. can be altered.

3.4 The Use of Lipid Nanomaterials in Encapsulation

According to (Zheng *et al.*, 2013), these colloidal nanocarriers offer several benefits, including stability, minimal toxicity, high drug concentration, and simplicity of target-specific release. Lipid nanocarriers include bulk nanocarriers, nanostructured lipid transporters, and nano emulsions (Gaber *et al.*, 2017). The specific benefit of lipid nano formulation is the avoidance of photodegradation (Nguyen *et al.*, 2012). Along with strong chemical degradation resistance, it can also comprise hydrophilic and hydrophobic Ais (Li *et al.*, 2018). The lipid-based NPs successfully carry AI to the target region and facilitate plant uptake (Kumar *et al.*, 2019). According to (Nakasato *et al.*, 2017), these nano formulations had no phytotoxic effects on seed germination or early plant development.

3.5 Encapsulation Using Clay Nanoparticles

The clay nanomaterial is utilized to gradually release active compounds. It features delayed release and a big AI loading capacity due to its larger surface area. According to (Cao *et al.*, 2017), AI pesticide loading is observed to be 20% higher than traditional pesticide loading. It has high photothermal stability, which offers the insecticides a lot of bioactivity (Kumar *et al.*, 2019) According to research conducted by (Fan *et al.*, 2017), Kasugamycin based on pectin cross-linked silica nano capsules shows high photothermal stability and AI loading. Over time, chlorantraniliprole insecticide based on mesoporous silica nanoparticles displayed strong AI loading, significant AI resistance, and severe mortality of Plutella xylostella larvae (Kaziem *et al.*, 2017) furthermore, clay-based nanoparticles.

4.1 Nitrogen-Doped TiO2 Based Nanopesticides

A new agri-tech advancement has just recently begun to increase agricultural capacity in order to meet the world's expanding food demand. Engineering nanomaterials have the potential to increase agricultural efficiency, resilience, and sustainability while also having a beneficial impact on the environment. Nitrogen-doped nanoparticles (N-doped NPs) are crucial. Acaricide resistance is a critical agrochemical restriction in the development and deployment of Nanopesticides towards effective and environmentally friendly agriculture. Efficiency improvements, new insect control concepts, and reduced pricing are all essential agrochemical restraints. The key benefits of N-doped Nanoparticles are their versatility, which allows for increased adhesion of leaves or insects entities, and they have multiple types of action used for killing insect species, comprising biochemical, stimulating, and electrochemical, which are predicted to be considerably decreased in insects. In addition to insects, these nanoparticles can prevent phytopathogenic bacteria and fungus action via a multitude of mechanisms variety of procedures and thus beneficial for a variety of plant protection. Due to their exceptional photocatalytic properties this feature produces a variety of reactive oxygen species. TiO2 nanoparticles have become widely used in the reduction of growth. ROS from weeds, bacteria, fungus, and other plant diseases. This Doping with has also substantially improved this trait. Nitrogen is used to kill germs and fungi. As an example, metal nano catalysts with nitrogen-doped oxides (Liu *et al.*, 2007) the chemical reactions of TiO2 and n-doped TiO2 nanoparticles via Escherichia coli bacteria were studied in the dark. As a result, photo electrocatalytic nanoparticles are no longer useful. There is a discernible effect on bacterial decrease. Alternatively, N doped TiO2 demonstrates a considerable increase in E. coli neutralization. Afterwards a 120-minute span of illuminating, germs were found. Another study is being undertaken to determine the effectiveness of various nitrogen sources are used to inhibit Escherichia coli bacteria. The findings show that N-doped TiO2 nanoparticles made with ethylenediamine as a precursor inhibited E. coli growth. The best outcomes are obtained within 90 minutes. Meanwhile, ethanolamine-derived N-doped TiO2 NPs greatly increased E. coli inhibition. This is known to be the case. Due to the Ti-N connections observed in N-doped TiO2 NPs. Furthermore, the Ti-N bond is hypothesized to facilitate the interaction of electrons between titanium in TiO2 NPs and nitrogen doping induces a change in electron structure at the valence band edge. As a consequence, the energy of TiO2 has increased. Another source of evidence is presented to describe the E. coli photocatalytic inactivation technique employing N-doped TiO2 (Janus *et al.*, 2019)

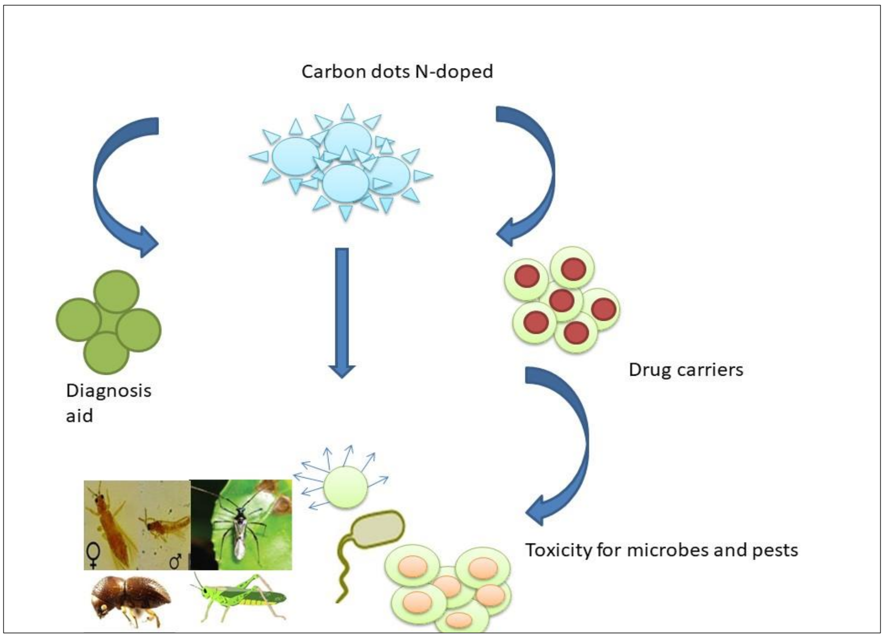


Fig. 4.1: Benefits of using N-doped CDs, N-doped CDs are employed in illness detection, as carriers for medications that kill germs and pests, and have a direct impact on pests

4.2 Cost Analysis of Nanopesticides

Nanotechnology-based techniques have shown promising outcomes for agricultural sustainability, particularly in fertilizer and pesticide innovation. It is important to assess economic factors and of these nanoformulations. Crop demand is predicted to rise dramatically in the future decades due to the growing worldwide population. Over the last 70 years, wheat and rice production has consistently increased. However, vegetable, fruit, soybean, and rubber plant productivity has grown quicker. Using conventional pesticides to improve crop yields is no longer effective and has caused severe environmental damage. Excessive application approximately 10-70% of pesticides are sprayed to plants, whereas less than 0.1% may reach biological targets (Zhao *et al.*, 2017).

The cost-benefit study of nanopesticides shows that existing nanoformulations have the potential to increase agricultural revenue while reducing environmental effect. However, more efficiency improvements are needed for widespread use. Developing nanoformulations for targeted distribution, reducing greenhouse gas emissions, and limiting nanomaterial content in pesticides can provide significant environmental and financial advantages (Su *et al.*, 2022).

In 2019, FAOSTAT reported that the global pesticide use in agriculture was approximately 4.17 million tonnes, including 2.22 million tonnes of herbicide.0.70 million tonnes of insecticides and 0.97 million tonnes of bactericides and fungicides. Nanotechnology has the potential to lessen the environmental impact of herbicides, given their widespread use. Nanoformulations include nanoporous materials like SiO2 and zeolites, nanomicelles (self-assembled amphipathic polymers), and nanoemulsion.Potential pesticide carriers include emulsions made from oil in water and polymeric nanocapsules (Kong *et al.*, 2018). However, there has been minimal focus on developing nanocarriers for effective pesticide administration and in vivo release. The financial viability of substituting conventional pesticides with nano-encapsulated pesticides remains unknown and requires more exploration as more data is available. We compared the effectiveness of conventional pesticides with nanopesticides (in two categories: pesticides in metal-based and pesticides in nanocarriers) in inhibiting pathogens. Nanocarrier pesticides outperform traditional formulations under various conditions, with an average efficiency improvement of 25.4 ± 11.6% at the same dosage (Su *et al.*, 2022).

Nanopesticides have a significantly lower lethal concentration (LC50) than traditional pesticides, sometimes by an order of magnitude. Nanopesticides offer cost benefits due to their reduced active component mass, which varies across different products. Given the comparatively low cost of effective nanocarriers materials include nanocellulose ($1-50/kg), alginic acid ($1-6/kg), nanochitosan ($11-34/kg), and zein ($40-50/kg). Organic nanocarriers are likely to be cost-effective for pesticide delivery. Nanopesticides with lower LC50 may be hazardous to species in their environment, prompting further research before practical application. Metal-based nanopesticides include Ag, Zn, and other metals including as Ti and Mg. We obtained LC50 values for the aforementioned nanopesticides against many types of microbes, Fungi, and Pests. Metal-based nanoparticles can effectively manage pests and pathogens in agriculture, offering advantages over traditional methods including lower LC50 (Wang *et al.*, 2022).

Metal-based nanopesticides vary in effectiveness, making it impossible to determine a universal operating concentration based on their LC50. Metal-based nanopesticides may be more effective when mixed with secondary metals, biosynthesized with plant extracts, or combined with conventional pesticides The cost of 378.5 l (100 gallons) of conventional pesticide solution ranges from $1 to $160, with active ingredient concentrations ranging from 0.1 to 3.0 mg/l (Bowling *et al.*, 2020). The cost of nanopesticides (nAg, nTiO2, nZnO,and nCuO) per 378.5 l suspension ranges from $1.14 to $303, $0.3 to $68.22, and $0.038 to $40respectively. For instance, if a nanopesticide costs $100 kg−1 and has an effective concentration of 100 mg l−1, the cost is approximately $0.01 l−1 (or $3.79 every 378.5 l). This is far cheaper than the price of most traditionalpesticides. Nanoparticles (NPs) can help degrade pesticides, reducing their environmental impact in lieu of reducing their dosage (Xue *et al.*, 2014).

Minimizing nanomaterial dosage is crucial for reducing costs and environmental impact, highlighting the genuine benefits of nanopesticides. Developing efficient techniques for NP transport in the field is crucial, as traditional methods like leaf spraying and soaking the soil lead to inefficient NP uptake and increased risk of environmental leaching. Trunk injection and petiole/branch feeding are effective methods for delivering nanoparticles into larger trees. Evaluating the cost of nanoformulation delivery systems is crucial for implementation (Su *et al.*, 2022).

5.1 Analysis of Nanopesticides' Environmental Risks and Benefits

In the majority of nations throughout the world, a pesticide's environmental risk assessment is already necessary before an item is released to the public. As a result, Nanopesticides are going to be tested similar regulatory system as traditional, non-nano scale pesticides, but with an emphasis on the nanoscale's specific properties. Pesticides comprising nano-silver /metal oxides have been considered in this respect by the Scientific Advisory Panel of the United States Federal Fungicide, Insecticide, and Rat killer Act. (FIFRA). The Panel reasoned that present approaches may not be sufficient to address or forecast the environmental fate and consequences, and that Such nanoparticles' possible hazards to human health and the environment may differ from those offered by regular pesticides.

Fig. 5.1: Health and environmental risk assessment of pesticides

In Europe, number of horizontally (cross-sector) as well as vertically sector regulatory structures have already been put in place to assess and manage the risk that nanomaterials represent to the welfare of humans and the natural environment. Plant preservation chemicals must need prior authorization before being put on the market and are primarily governed by Regulation (EC) No. 1107/2009 (Kookana *et al.*, 2014). Additionally, the legal framework for the use of nanotechnology-based products for agriculture differs by nation in many regions, particularly Asia, Africa, and Oceania (Subramanian and Rajkishore, 2018). For instance, the In India, 'Instructions for assessment of nano-agri products were recently published, specifying nanopesticides & nanofertilizers, whereas legislative and regulatory structures have yet to be developed (Mishra and Patni, 2022).

However, because this subject is still in its infancy, the majority of nations are still debating how best to regulate nanopesticides. It's also crucial to remember that, in the absence of evidence or sound scientific justification, one should not presume that a nanopesticide's characteristics and behaviours are equivalent to those of its traditional counterpart. This is due to the possibility of changes in a substance's characteristics behaviour, when compared to their equivalent traditional forms (Pérez-de-Luque, 2017; Santiago *et al.*, 2020). Additionally, a pesticide's (eco)toxicological effects may also result from a considerable alteration in its physicochemical properties at the nanoscale because of conjugation or formation of complexes with the environment's population of microbes or macromolecules (Vryzas, 2016). The essential elements that necessitate nano-specific concerns in the threat evaluation of nanomaterials (also relevant to nanopesticides) were recently detailed in a recent EFSA Opinion (Committee *et al.*, 2018)

5.2 Environmental fate of Conventional pesticides and Nanopesticides

When assessing the danger of nanopesticides, it is critical to consider their ongoing existence, actions, and destiny into the environment. The following nanopesticides use scenarios are conceivable: A conventional (non-nano) formulation's release profile, as well as Because it is solely utilized as a means of transport for pesticide active components and degrades fast in surroundings, the separation and stability of active components in diverse environmental media are equivalent with those of the nano formulation. The same risk evaluation process used for conventional pesticides should be employed in these situations. The use of a significantly higher amount of co-formulant(s) in the nano-scale formulation/encapsulation compared to the traditional formulation may must be taken into consideration, though. If so, it is also important to take into account how safe the co-formulants are at the current dosages. Because the active component may get chemically attached to other substances while in the encapsulation procedure, the dissolution of active component (s) from the nano formulation is possibly very gradual or very partial because of the encapsulates' incomplete breakdown in the atmosphere. Because the carrier fragments may differ from the active with regard to chemical makeup, characteristics, and individual component impacts. Due to its resistance to degradation, the nanopesticides not discharge its active components. Except in cases when a pesticide is intended to be persistent (for example, when used to treat wood to prevent termites), this may be an improbable occurrence. In most other situations, it is necessary for pesticides to release post-application at a specific rate in order to sustain activity against the intended pests. This may be important to estimate the possible concentration of persistent nanopesticides in the surroundings and in food chain. It is probable that the same important elements that are taken into account for traditional (non-nano) pesticides will have a significant impact on how nanopesticides behave inside the environment (Vryzas, 2018). These include the sedimentation and suspension of an aquatic compartment, as well as decomposition by physical, chemical, or biological means (enzymes, underwater microbes, floating animals and species of plants, sunshine, oxidation, hydrolysis, and so on). According to research, the bulk of the physicochemical as well as environmental factors that might impact the destiny and functioning of nanoparticles are shared by different types of materials. For example: Consider the following characteristics regarding the soil section: the kind of soil, permeability, water flow, composition of minerals, pH, bacterial population, temperature, quantity and kind of naturally occurring organic matter, particularly organic acids such as humic, and electrolytes (especially bivalent cations). For the aqueous compartment, PH, salt content, ionic concentration, dissolved (and dispersed) organic material, and microbes are measured.

The constant interaction of nanomaterials with the nearby media in their environment, as well as the absorption/adsorption of various moieties on particle surfaces, may potentially induce a change in particle characteristics. The surface binding of naturally occurring organic materials is a significant one (Grillo *et al.*, 2015), especially humic acids (Liu *et al.*, 2010; Wang *et al.*, 2012).

As a result, mineral soils are more likely to have mobile nanoparticles than soils with large levels of organic matter. It is also known that the existence of ions, particularly bivalent cations, in the environment can alter the way that nanoparticles aggregate (Liu *et al.*, 2011). This implies that a nanomaterial's behavior in freshwater versus seawater may change.

Nanomaterials' fate, action, and perseverance in the surrounding environment can all be greatly influenced by the biotransformation that occurs in the environment as a result of interaction with biofilms, biological organisms, and plants. For example, (Booth *et al.*, 2013) investigated the clustering action of polymeric nanoparticles based on methacrylates. They discovered that their behavior in aquatic environments can be significantly influenced by Salinity, component chemistry, quantity, and the type of stabilized agent utilized in synthesis. Although it has not previously been thought of as a consideration, current investigations have highlighted the significance of the nanoparticle ageing while examining their fate and behaviors into the environment (Mitrano and Nowack, 2017)

The hypothetical displacement of nano-sized transporters via GI tract is conceivable in regard to the biokinetics of Nanopesticides. This appears to be the case, though, if the nanoparticles lack strongly charged polymers are resistant to being broken down into the digestive tract. The gastrointestinal system can translocate submicron-sized delivery vehicles, according to studies on the nanocarriers used for medication delivery. For polymeric nanoparticles, it has been assumed that cellular absorption occurs mostly by endocytosis, and the vehicle's destiny is determined by the polymer's stability and the form of nanoparticle (Plapied *et al.*, 2011) Additionally, Nanopesticides are investigated in plants and intended organisms (insects) (Shahzad and Manzoor, 2021) For example, the epidermal and endodermal of sugar maple roots contained positively charged zein nanoparticles with a diameter of about 130 nm. While atrazine-containing nanoparticles made of poly-epsiloncaprolactone with a diameter of around 250 nm stuck to the leaves of Brassica juncea plants and entered the mesophyll tissue (Phanse *et al.*, 2015; Bombo *et al.*, 2019) The creation of either positively or negatively charged particles as a vehicle for the transmission of the mosquitocidal double-strand in mosquitos, as well as the study of their biological distribution in pupae and cells. According to their research, negatively charged nanoparticles persisted throughout insect metamorphosis and were primarily found in the body, and adults ovaries. Positively charged nanoparticles, on the other hand, had improved gastrointestinal tract contact, in vitro cell internalisation, and cytosol dispersion.

5.3 One of Nanopesticides' Health Concerns

Nanoparticles are now equally vital for bacteria and ticks (Sarwar *et al.*, 2021). As the use of Nanopesticides grew more common, questions about how to evaluate the environmental impact of these resources arose. The provide strategies for measuring pesticide environmental risk are reread, and the question of whether these strategies are appropriate. There has been a lot of discussion about using nanopesticides in practice. The sensitivity of compositions based on nanoscales and their practice surrounding repercussions are key issues that has to be handled. The number of nano formulations found in soil and on the surface water, and their impacts on nontarget species creatures, are not well understood. Nano formulations' Futuremay be altered by a number of chemical factors such as pH, ionic strength, or the number of dissolved compounds in the surrounding atmosphere are all factors to consider. Pesticide movement off-site Pesticide runoff to the surface is reduced when pesticides are dissolved. The toxicity of a range of insecticides used in nanoscale compositions was investigated, as well as the potential negative consequences and ramifications. Nano dimensions have to be taken into account while nano scale formulations. The most essential factor for evaluating the dangers is the environmental persistence of Nanopesticides related with their usage. Nontarget creatures are subjected when emancipation or release is blocked for an increased period of time. One of the potentially negative impacts of nanocarriers is to encourage the transformation of some immobilized components that are functioning. Because of this, organisms may be exposed to them more frequently. Certain nano formulations have been developed. It has been found to increase absorption by target species. It has to beIt has been confirmed that no nontarget creatures have been injured. Insecticides are evaluated in the same way as other poisons are. Because the Trojan horse activity results in a Nanopesticides to engage with other polluters, risk assessment of Ecological interaction is frequently underestimated. As a result of this because of the chemical's interaction with ENP, the compound is given to an animal tissue increasing the exposure of interior to contaminants and potentially keeping the accumulation at bay. The time has come to incorporate these relationships.

5.4 Barriers of using Nanopesticides

The possible harmful environmental consequences of nanoparticles remain unclear, therefore assessing the dispersion and behavior of nanopesticides both before and after implementation to the surroundings is critical for understanding their possible effect on ecosystems (Isigonis *et al.*, 2019) complex testing methods are required. Nanopesticides are expected to perform actions differently from regular insecticides, and some usual ERA strategies may be ineffective. Nanopesticides are a type of pesticide. As a result, new testing approaches have emerged. To analyse the environmental state, many measures may be necessary. Nanopesticides are dangerous. Whereas it might be possible in certain circumstances to develop stringent testing methodologies and modelling tactics that correctly determine sensitivity and specificity, the effects of a nanopesticides in a certain scenario cannot be predicted. It is equally important to recognize that existing approaches for conventional pesticide risk assessment that employs several. To resolve misunderstandings, presumptions are rarely used Flawless. A rational method that accounts for the basic disparities between nanopesticides and traditional pesticides is required to go ahead in a feasible and achievable way (Kookana *et al.*, 2014). Nanopesticides have been proven to travel, bioaccumulate, and degrade differently than standard pesticides. There is a scarcity of research on the impacts of nanoparticle pesticides on the health of crops, biodiversity in soil, nontarget organisms, and the well-being of humans (Kah *et al.*, 2018; Xu *et al.*, 2019)

5.5 Nanopesticides; Applications, Challenges and Future Perspectives

The literature clearly indicates that nanopesticides offer multiple advantages over conventional pesticides, for instance, increased potency, cost-effectiveness, and improved safety for users and the environment. Agricultural and postharvest diseases and pests have a substantial impact on both crop reduction and farmer revenue. Farmers mostly utilize chemical-based pesticides for managing pests in order to maximize crop production, which pose possible threats to employees, customers, and the environment. Metal based nanopesticides have the potential to be less toxic than traditional pesticides in plant protection, whereas essential oils and biologically active based nanopesticides, as well as control released formulations, have the possibility of use in the production of organic food and environmentally conscious farming. Nanoparticles and/or nanoemulsions containing nanomatrices of metallic substances, agrochemicals, natural oils, and biologically active substances in nanopesticide compositions have been manufactured and tested for efficacy against diseases and pests (Djiwanti and Kaushik, 2019).

This suggests promising practical applications for nanopesticides in agriculture. Essentially, by replacing conventional pesticides with nanopesticides while maintaining the same agricultural practices, we can increase the benefits of these advanced formulations. Although there is a cost associated with transitioning from conventional to nanopesticides, the advantages they offer far outweigh this expense, making them a valuable choice for both human health and environmental well-being. Pesticide spraying releases organic solvents and harmful substances into the environment, leading to soil and water pollution, crop residues and a possible harm to human health (Hayles *et al.*, 2017).

Pesticide regulations vary from country to country, and many AI-powered pesticides fall under specific regulatory frameworks for agricultural use. From seed technologies to horticultural operations, field investigations, and after harvesting procedures, conducting residual and efficacy analyses, along with nanotoxicology assessments, is crucial for obtaining commercialization licenses. These licenses cover various aspects, including production, storage, sale, and usage in the agriculture sector. However, the costs associated with legal fees and other related expenses can be substantial, posing a limitation to the widespread availability of new nanopesticides. There is currently no product based on nanotechnology in the market, despite the fact that it has many potential advantages over ticks. The large amount of continuous research being carried out at research institutes and by small businesses, to determine the nanomaterials' affordability at the population level, is one factor leading to the low level of industrialization. At the same time, large firms possess a significant number of patents, and this number continues to rise. Because major corporations accumulate copyrights and look for prospects for future usage after developing enticing business items, novel nano-based items are not introduced to the market (Camara *et al.*, 2019).

i. Consumer acceptance and awareness
ii. Scalability
iii. Funding organizations must purchase these concepts.
iv. Application ease, frequency, and dosage could all be considered.
v. It is critical to encourage research into nontarget effects on host animals and other organisms.

It should be noted that cost issues remain a key impediment to the advancement of nanopesticides contrast to the constraints mentioned above. Nanopesticides development requires significant upfront costs, and it is still far from practicable to use these chemicals in sufficient numbers to generate a profit. In addition, a significant impediment to the utilisation of nanotechnology in cattle is a lack of regulation. The expensive cost is another impediment to the development of insecticides based on nanotechnology. (Handford *et al.*, 2014) Another challenge lies in persuading the public and farmers to switch from their familiar existing products to these new Nanopesticides. Marketing efforts, such as advertising, are essential to establish these products in the market, even though this aspect falls outside the realm of scientific work but is necessary for successful adoption.

Nanotechnology has the potential to boost agricultural profitability, particularly for high-value crops, while reducing the environmental impact of traditional pesticides. Nanoformulations have low efficiency but high cost, allowing for partial replacement of conventional counterparts for increased revenue and environmental benefits. Further enhancing the effective use of nanoformulations is required for widespread deployment. Previous research has mostly examined the effectiveness of nanopesticides on crops for human use, such as grains, fruits and vegetables, with few studies conducted on animal nutrition, fruit plants, and non-food crops. The next phase of research should focus on improving the efficiency of harmless nano-agents for environmental as well as economic advantages, long-term monitoring of nanoparticles in surroundings and vegetation, developing efficient NP delivery strategies and controls for nanomaterial consumption should align with their potential harm to human health (Su *et al.*, 2022).

CONCLUSION

The toxicity mechanism of nanopesticides and their global harmful effects remain poor as compared to conventional pesticides. The effects of nanopesticides might vary depends on particular characteristics of nanoscale carrier and AcI; yet there's currently minimal chance for rapid changes. This must be taken into account while weighing the advantages and disadvantages. The development of pathogens that act as barrier to fungicides and antibacterial is currently a concern. Current views, on the other hand, provide feasible answers to this problem, such as pesticides derived from nanoparticles with numerous antimicrobial modes of action. The novel properties raise concerning nanopesticides' environmental destiny and disposal, as well as their interaction with pollinators. Pesticides impact on the populations of aquatic invertebrates and dwindling insects is a growing global concern. Pollinating insects have a crucial role in the agricultural ecology, especially for human subsistence, as they are in charge of the majority of the pollination of crops. Technology-based pesticides using a variety of materials have been developed as a part of experimental research.

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