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Advancements in nanotechnology for sustainable pest control in agriculture

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Abstract
The combination of insects, mites, nematodes, and diseases is what we often refer to as agricultural pests, and controlling them effectively is necessary to ensure maximum crop productivity. However, an over-reliance on pesticides leads to negative consequences such as crop residue accumulation, resistance development, and environmental degradation. Alternative pest management techniques are desperately needed in the current environment to sustainably boost agricultural output. With its many uses in fields including engineering, medicine, electronics, pharmaceuticals, and agriculture, nanotechnology appears to be a viable solution to this problem.

When applied to pest management, nanotechnology enables precise control and targeted delivery of agrochemicals. It also provides diagnostic tools for the early detection of pests. Importantly, nanoparticles are biodegradable and environmentally friendly. The slow release of encapsulated functional molecules in nano-based pesticides eliminates the need for frequent applications. Additionally, incorporating nano-materials into the matrix of a substance prevents adverse reactions to external factors like air or light. Consequently, nano-based agrochemicals emerge as efficient alternatives for managing insect pests in agriculture without causing harm to nature. This article explores the potential of nanomaterials within current nanotechnology methods for insect pest management."

Keywords: Insects, nanotechnology, agrochemicals, targeted delivery, biodegradable

Introduction
One of the dimensions at the nano scale range is exhibited by the nano material. Because the word nano signifies a billionth of a unit, the nano scale is commonly defined as a range of 1-100 nanometers. Nanomaterials are categorised into three types: 0-D nanoparticles (bucky ball, for example); 1-D nanowires, nanotubes, and nanorods; 2-D nano films and nano coatings. The Greek word nanos, which meaning midget, is where the word nano first appeared. In science, the word "nano" stands for 10^{-9}, and one nanometer is one millionth of a millimetre. Because of their size, these materials differ from bulk (or micrometric and bigger) materials in terms of their unique characteristics, which include chemical reactivity, physical strength, optical effects, magnetism, and electrical conductivity (Bhattacharyya *et al*., 2010) [5]. All branches of science may find use for these characteristics. The multidisciplinary fusion of material science, chemical processing, biotechnology, nanotechnology, and system engineering to create nano-biomaterials, nanocrystals, biochips, and molecular motors is known as nano-biotechnology (Huang *et al*. 2006) [12]. Top-down and bottom-up techniques are the foundation of nanotechnology. By etching from the bulk material down to the order of nm, the top-down method creates progressively smaller structures. Nanomaterials are created by a bottom-up technique, which involves assembling ingredients atom by atom or molecule by molecule.

Crop output in agriculture suffers large losses as a result of weeds (both monocot and dicot), arthropod pests (insects, arachnids, rodents, and birds), and plant pathogens (fungi, bacteria, and viruses). Arthropod pests, in particular, play a critical role in causing significant losses by directly feeding on host plants and functioning as vectors for a variety of infectious illnesses. Insect pest management options include cultural, physical, behavioral, biological, and chemical techniques.

However, farmers' dependence on chemical insecticides is widespread, owing to their ease of availability and immediate efficacy. The repeated use of these chemical agents, on the other hand, results in the formation of problems such as resistance, resurgence, and residue, sometimes known as the 3R's. As a result, there is an urgent need for the investigation and development of new, modern pest management approaches. The use of nanotechnology in agriculture appears to be a promising frontier, providing efficient and novel answers to the aforementioned difficulties.

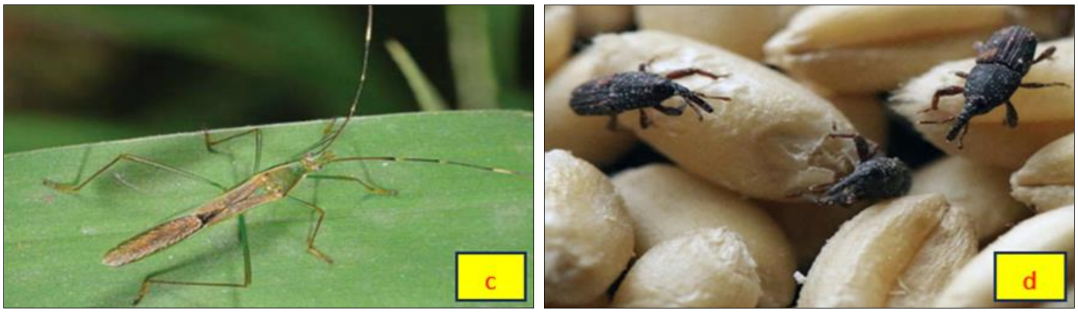

Fig: Some of the common insect pests of India. a: *Acryrthosiphon sp.,* b: *Spodoptera sp.,* c: *Leptocorisa sp.,* d: *Sitophilus sp.*

Exploring the Applications of Nano-Scale Wonders

Nano-pesticides are made up of a wide range of materials, including organic elements like polymers and inorganic components like metal oxides, which can be found in various shapes like grains or micelles. These nano-formulations perform a variety of critical functions, including increasing the apparent solubility of poorly soluble active compounds, ensuring the gradual and consistent release of active ingredients, protecting these ingredients from degradation, and assessing the presence of enzyme activity in a system (Thakur *et al*., 2018). To improve efficacy, the necessary compounds or components can be synthesised in nanoparticle form or size.

These impacts can improve particle characteristics or reduce the material's functional capabilities. Nano-active materials suffer a variety of changes, including an increase in surface area to volume ratio, exposure to quantum mechanical effects, dominance over electromagnetic forces, and the potential for random Brownian motion (Rani and Sushil, 2018) [22]. The use of nanoparticles allows for the exact application of insecticides, which target specific pests or illnesses as well as specific plant locations. This accuracy corresponds to the function of controlled pesticide release systems in agricultural areas. The goal is to gradually reduce or minimize pesticide demand in crops, ensuring effectiveness and safe pesticide usage using intelligent designs that regulate and slow pesticide release (Huang *et al*., 2018) [11]. Implementing a controlled release strategy for nano-pesticides within the plant system allows for slow, purposeful release rather than a reactive response to environmental variables. Precision pesticide release, considering parameters such as light, temperature, relative humidity, wind velocity, and direction, holds the promise of improving the overall effectiveness and efficiency of pesticide application. A good example is the chemical compound pyraclostrobin, which has been shown to be effective against blast fungus in rice harvests. This chemical causes physiological changes in plants, enhancing their resistance to disease while also increasing agricultural yields. Furthermore, the addition of porous SiO_2 nano-spheres improves pesticide action time, stability, and efficacy against pathogens (Huang *et al*., 2018) [11].

These nano-formulations are known as smart microcapsules (Murugan *et al*. 2016) [18]. Nanomaterials such as polymers, crystals, and semiconductors are gaining popularity due to their unique optical, electromagnetic, and electrical capabilities. Microbiological production of nanoparticles is a fast-expanding topic of active nano-technology study around the world. The creation of nanoparticles involves the use of simple prokaryotes to complex eukaryotic organisms seen in higher plants. The synthesis of key plant nutrients including Mg, Zn, Ag, Ti, P, and Fe nanoparticles from various fungal species was found to be more stable due to spontaneous encapsulation by mother proteins. It is true that a protein can be used to make nanoparticles.

Dynamic light scattering, transmission electron microscopy (TEM), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy, and zeta potential analysis were employed to describe the nanoparticles. These procedures enabled the nanoparticles' concentration, size, and form to be adjusted for agricultural spraying. Margulis-Goshen and Magdassi (2013) [17] explain the techniques required to prepare nano-formulations in detail. Nano P, Zn, Mg, and Fe applications enhanced grain crop yields by 12.54% and 18.39% in dry matter yield, respectively, across 11 different crops. The efficiency of nutrient consumption rose thrice when nano-fertilizers were used instead of conventional fertilisers. Researchers have confirmed that feeding mice food made with nano-fertilizers has no toxicological impact on the animals (Tarafdar and Raliya, 2012; Parisi *et al*., 2015; Rathore and Tarafdar, 2016) [21, 26]

Materials like polymer nanocomposites and nano-clay nanocomposites can be coated and loaded with *Pseudomonas sp.* or *Trichoderma sp*. in the expanding field of nano-scale carriers in nanotechnology (Ammar, 2018) [1]. The development of nano-chops and microarrays that can accurately and specifically identify minute nucleotide changes in bacteria and viruses is another advancement highlighted by Ammar (2018) [1]. The study conducted by Gutiérrez *et al*. (2008) [10] focused on nano-emulsions, which are composed of oil/water droplets with a size of less than 100 nm. By means of covalent attachment, adsorption, encapsulation, and entrapment inside nanoparticles, different ligands have been able to efficiently load different active pesticide chemicals onto nanoparticles. According to Athanassiou *et al*., (2018) [3], the controlled and gradual release of active compounds is feasible because of the nano-carrier's degrading properties and interactions with other substances.

Concerns have been raised about nanoparticle absorption by the plant system and the potential impact on plant growth and development. Numerous studies have been conducted to investigate the ease with which nanoparticles can penetrate plant internal systems and the consequent major changes in these systems. According to Rodriguez *et al*. (2016) [23], evaluations of the influence of nanoparticles on plants have primarily focused on germination and root elongation experiments. Carbon nanotubes have a favourable effect on tomato plants, according to Khodakovskaya *et al*. (2009) [14], contributing to improved seed growth and development. Furthermore, Yasur and Rani (2015) [32] discovered that treating castor seeds with silver nanoparticles had no effect on seed germination or attracted lepidopteran pests.

Insect-Mediated Nanoparticles

As Watson and Watson (2004) pointed out, the frequently disregarded nano-structures that are present in nature offer a useful resource to satisfy particular requirements. Insect compound eyes and wings contain many nanostructure elements, which enhance aerodynamic efficiency. Interestingly, different components in nanoparticles are responsible for the vivid colours seen on butterflies' wings. One excellent example is the cicada (Psaltoda *claripennis*), whose wings display well placed nanoparticles in the shape of hexagons (Zhang and Liu, 2006) [31]. The body surface of the Indian rock honey bee *Apis dorsata* has calcium silicate and calcium phosphate nanoparticles, which range in diameter from 5 to 50 nm. The wings have bigger nanoparticle sizes (20 nm) than the thorax and belly, which have nanoparticle sizes of about 10 nm (Bhattacharyya *et al*., 2016) [6].

Chemical and Biological Nanoparticles and Nanomaterials Against Insects

Chemical and biological nanoparticles in nanomaterial form have insecticidal characteristics and can successfully control insect infestations. Nano-silica sprays, for example, modify the feeding patterns of the cotton leaf worm, *Spodoptera littoralis*, which increases tomato plant resistance. As a result, female insects on tomato plants have reduced longevity, reproductive capacity, and fecundity, resulting in a decrease in insect population density, crop damage, and yield loss. El-Bendary and El-Helaly (2013) [9] found that silica nanoparticles considerably reduce insect populations and their negative influence on crop productivity. Furthermore, both silica and silver nanoparticles show exceptional efficiency against adults and larvae of the cowpea seed beetle, *Callosobruchus maculatus*, with mortality rates of 100% and 83%, respectively (Rouhani *et al*., 2012) [24].

Nanoemulsions (NES)

Due to traditional pesticides' low water solubility, nanoemulsions have been developed to improve their solubility and dispersal properties. Nanoemulsions provide various advantages over regular emulsions, including improved wettability, spreading, and mechanical stability of insecticides. As a result, nanoemulsions contribute to the long-term availability of insecticides by protecting them from UV light and inhibiting active ingredient volatilization, as highlighted by Mason *et al*. (2006) [16] and Anton *et al*. (2008). Furthermore, Wang *et al*. (2007) [30] found that nanoemulsion surfactants containing beta-cypermethrin are more stable than commercial beta-cypermethrin microemulsions. Anjali *et al*. (2010) [2] found that less water-dispersible nanopermethrin was required to attain the LC50 for *Culex quinquefasciatus* than conventional permethrin formulations.

Nanoencapsulation

Encapsulation is the process of confining nanoscale active substances into small envelopes or shells. This strategy ensures a steady and effective release of pesticides into the environment, which aids in insect pest management. Under certain pH settings, the release mechanism operates via diffusion, osmotic pressure, dissolution, and biodegradation (Vidyalakshmi *et al*., 2009) [28]. Sakulk *et al*. (2009) [25] found that encapsulated citronella oil nano-emulsion, made with a surfactant content of 2.5% and 100% glycerol, provided extended mosquito protection. The inclusion of glycerol improves stability and viscosity. Water-soluble insecticides can be effectively supplied by putting them into Porous Hollow Silica Nanoparticles (PHSNs) for gradual and controlled release. Nano-pesticides have also been developed utilising essential oil-loaded solid lipid nanoparticles (Liu *et al*. 2006).

Garlic essential oil is added to minuscule polyethylene glycol-coated particles. As a result, the oil is more effective against adult *Tribolium castaneum* insects in food that has been preserved. About 80% of the bugs are controlled by the oil that is slowly released by the particles (Yang *et al*., 2009). According to Patil's (2009) [19] research, alumino silicate adheres to both plants and insects when placed in small tubes. It has the ability to infiltrate the bodies of insects and disrupt their normal physiological processes. Rubber is used to encase chitosan, which is combined with specific acids and insecticides. These insecticides have a 35-day half-life after release, which is advantageous for enterprises that require controlled pesticide release (Rahim *et al*., 2016).

The seeds of the wild Indian almond tree, *Sterculia foetida*, were used to make silver nanoparticles encased in a mixture of proteins and lipids. It was discovered that these nanoparticles worked incredibly well against the larvae of mosquitoes such as *Culex quinquefasciatus*, *Aedes aegypti*, and *Anopheles stephensi*. Rajasekharreddy and Rani (2014) [20] found that these nanoparticles could remove larvae at concentrations as low as 4.5 ppm.

Nanopheromones

Pheromones are natural substances used by insects to communicate with one another. They hinder the insects' ability to discover and breed, making them useful for pest control while causing no harm to other beneficial insects (Campion *et al*., 1985; Thomson *et al*., 1999) [7, 27]. Each insect has its own distinct pheromone; therefore, beneficial insects are unaffected. However, pheromones deteriorate rapidly in nature due to sunlight, air, and their capacity to evaporate (Cork, 2004) [8]. Nanopheromones, which look like small jelly blobs, are the best choice for applying pheromones outside year-round, regardless of the weather.

According to Bhagat *et al*. (2013) [4], *Bactrocera dorsalis* can be controlled with the use of a unique jelly-like substance derived from the pheromone methyl eugenol (ME). This jelly stays powerful even when it's outside, and it slowly releases the pheromone, so you don't have to put additional pheromone out as often. It works well for controlling fruitflies. Likewise, Z-9 (Hexadecenal) and Z-11 (Hexadecanal) nanosex pheromones are useful in controlling *Scirpophaga incertulas*, the rice yellow stem borer. Compared to conventional pheromones, nanopheromones draw in more moths (Kannan, 2018) [13].

Conclusion

The application of nanotechnology in agriculture has the potential to significantly transform pest management techniques. Conventional pesticide use has resulted in a number of unfavourable outcomes, including the emergence of resistance, the buildup of residues, and pollution of the environment. Innovative pest management strategies are desperately needed to address these issues and guarantee sustainable crop production. Because it can distribute agrochemicals precisely and selectively and provide diagnostic tools for early pest detection, nanotechnology presents itself as a possible answer.

Compared to conventional techniques, nanoparticles have a number of benefits, such as biodegradability and environmentally beneficial properties. Functional chemicals are encapsulated in nano-based insecticides to ensure sustained potency while reducing the need for frequent treatments. Additionally, adding nanoparticles to pesticide formulations improves stability and reduces unfavourable interactions with outside elements like light and air.

Future research in nano-agriculture should focus on improving nanotechnology-based pest management strategies. This includes developing novel nanoformulations, improving our understanding of nanoparticle interactions with plant systems, and researching the long-term implications of nanoparticle use on crop productivity and environmental sustainability. With ongoing breakthroughs in nanotechnology, we may foresee a future in which agricultural pest management is both highly effective and environmentally responsible, ensuring the long-term viability of global food systems.

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