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Nanopesticides: Revolutionizing Pest Management with Nanotechnology

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ABSTRACT: Nanotechnology has emerged as a promising field with the potential to revolutionize various industries, including agriculture. In recent years, nanopesticides have gained significant attention as a novel approach to pest management. This review paper provides a comprehensive overview of nanopesticides and their impact on pest control practices. Nanopesticides refer to pesticide formulations that incorporate nanotechnology to enhance their properties and performance. The paper discusses the advantages of nanopesticides, including increased targeting efficiency, controlled release mechanisms, and improved efficacy against pests. It delves into the various nanomaterials used as nanopesticides, such as nanoparticles, nanocapsules, and various other nanoformulations, highlighting their unique characteristics and modes of action. The review also addresses the potential environmental and health implications associated with nanopesticide use, along with regulatory considerations. Furthermore, the paper explores the various other applications of nanotechnology in the field of agriculture such as soil remediation, water management, crop management, pesticide detection etc. It emphasizes the need for further research to evaluate the long-term effects of nanopesticides on ecosystems and non-target organisms. Additionally, the review paper discusses the challenges and barriers in the commercialization and adoption of nanopesticides, including cost-effectiveness and public acceptance. The paper concludes by emphasizing the potential of nanotechnology to revolutionize pest management by providing effective and sustainable solutions. It calls for continued research, collaboration among stakeholders, and the development of appropriate regulatory frameworks to ensure the responsible and safe implementation of nanopesticides in agriculture.

Keywords: Advanced pest management strategies, controlled release, nanoencapsulation, nanoformulation, nanopesticide, nanosensors, sustainable agriculture.

INTRODUCTION

Nanotechnology, the science and engineering of materials at the nanoscale level, has been revolutionizing various fields, and agriculture is no exception. In the realm of pest management, nanotechnology has emerged as a promising approach that holds great potential for addressing the challenges faced by modern-day agriculture. With the increasing global demand for food production and the need to mitigate crop losses caused by insect pests, innovative solutions are essential. Nanotechnology offers a range of tools and strategies that can revolutionize pest management practices by improving the efficacy, efficiency, and environmental sustainability of pesticide applications (Hofmann *et al*., 2020). One of the key advantages of nanotechnology in pest management is the ability to enhance the targeted delivery and controlled release of active ingredients (Hajji-Hedfi and Chhipa 2021). Nanoformulations enable the encapsulation of pesticides within nanoparticles, which allows precise targeting of pests thereby minimizing off-target effects. Nanoencapsulation has the potential to significantly improve the effectiveness of pest control for longer periods. This is achieved by safeguarding the active ingredients (AIs) from early degradation caused by challenging environmental conditions. The study conducted by Kumar *et al*. in 2019 highlights this promising aspect of nanoencapsulation. Nanomaterials facilitates the improvement of the stability and dispersion of active ingredients, promotes the precise delivery of agrochemicals, reduces residual pollution and decreases labor cost (An *et al*., 2022). Other benefits include enhanced solubility of water-insoluble active ingredients, improved formulation stability, elimination of toxic organic solvents commonly found in conventional pesticides, the ability to achieve controlled release of active ingredients, enhanced mobility and insecticidal activity due to smaller particle size and larger surface area, and prolonged effectiveness (Sasson *et al*., 2007).

Moreover, nanotechnology offers the potential for reducing the environmental impact of pest management practices by reducing the quantity of pesticides required (Zannat *et al*., 2022). This approach aims to minimize the negative impacts on soil health and biodiversity, while simultaneously improving soil function and nutrient cycling through the promotion of beneficial microbial communities, including optimized nitrifying and denitrifying bacteria (Zhang *et al*., 2021). However, the adoption of nanopesticides also raises important safety considerations and regulatory challenges. It is crucial to assess the potential risks associated with nanomaterials, including their toxicity, persistence, and potential for bioaccumulation in the environment (Kah *et al*., 2018).

Use of nanotechnology in pest management

The use of nanotechnology in pest management has shown promising results in providing effective and sustainable solutions. Nanoparticles, with their unique physical and chemical properties, offer new avenues for targeted pest control. Nanoparticles have demonstrated effectiveness as toxicants, repellents, and growth retardants against various insect pest species, with notable mosquitocidal activity. The utilization of green synthesized nanoparticles employing plants as both reducing and capping agents, has been shown to induce mortality in mosquitoes at different stages of development, including eggs, larvae, and adults by Pathipati and Kanurparthi (2021). Additionally, these green-synthesized nanoparticles exhibit acute toxicity, fumigant properties, anti-feedant effects, repellency, attractancy, and reproductive inhibition against agricultural and stored product pests, all at lower doses compared to chemically synthesized nanoparticles. Silica (SiO_2) nanoparticles (NPs) have gained significant interest as potential alternatives to conventional insecticides among nanomaterials (Thabet *et al*., 2021). The insecticidal effects of silica NPs are believed to occur through direct abrasion of the insect cuticle or absorption into the cuticular layers (Ayoub *et al*., 2017). They further investigated the significant insecticidal effects of silica nanostructures on the cotton leafworm (*Spodoptera littoralis*) using surface contact and feeding bioassay methods. Furthermore, it was observed that the deceased insects exhibited severe dehydration, which could be attributed to the damage caused to the insect's cuticular water barrier as a result of abrasion. Moreover, silica NPs might indirectly impact pests by obstructing their digestive tracts when they feed on treated plants or food. Additionally, the application of silica NPs could lead to the malformation of external morphology in pests. In the case of insect herbivores consuming silica-treated plants, silica may also disrupt their digestive tracts (Smith, 1969). The use of SiO_2 and aluminium oxide (Al_2O_3) nanoparticles can be considered as a suitable alternative method for protecting stored grains, serving as an alternative to chemical insecticides. Smith (1969) further reported that these nanoparticles are relatively safer for human use compared to substances like malathion.

The effectiveness of inorganic nanoparticles, including Cadmium sulfide (CdS), Nano-silver (Nano-Ag), and Nano-titanium dioxide (Nano- TiO_2), against *Spodoptera litura* has been demonstrated by Chakravarthy *et al*. (2012). The effective control of fruit fly, *Bactrocera dorsalis* has been achieved through the utilization of a nanogel prepared from the pheromone methyl eugenol (ME) (Bhagat *et al*., 2013). Malaikozhundan *et al*. (2017) through their experiment reported that *Bt* coated zinc oxide nanoparticle are effective against *Callosobruchus maculatus* and could be used as nanobiopesticides in the control of stored grain insect pests in the future. Benelli, (2018) in his study reported that silver and graphene oxide nanoparticles exhibit notable effects on insect antioxidant and detoxifying enzymes, resulting in oxidative stress and cellular demise. Additionally, silver nanoparticles decrease acetylcholinesterase activity, while polystyrene nanoparticles impede CYP450 isoenzymes. Benelli (2018) further reported that gold nanoparticles function as trypsin inhibitors, disrupting insect development and reproduction. These metal nanoparticles can bind to sulfur (S) and phosphorus (P) in proteins and nucleic acids, respectively, causing reduced membrane permeability, organelle dysfunction, enzyme denaturation, and ultimately cell death (Benelli, 2018). In their study Wang *et al*. (2022) reported that in comparison to non-nanoscale pesticides, nanopesticides demonstrate a significant improvement in overall efficacy against target organisms, with a 31.5 per cent higher effectiveness observed. Field trials further revealed an 18.9 per cent increase in efficacy. Importantly, nanopesticides exhibit a considerably lower toxicity of 43.1 per cent towards non-target organisms, indicating a reduction in environmental collateral damage.

The field of agricultural pest management has witnessed diverse applications of nanotechnology, including the following.

Smart Pest Monitoring. Nanosensors can be developed to detect and monitor insect pests in real-time. Nanosensors can detect the presence of pests by identifying their unique biomarkers, such as pheromones, enzymes, or specific chemicals emitted by pests. Martinazzo *et al*. (2022) conducted an invivo experiment where gas nanosensor was used for detecting pheromone and its interferent compounds in *Euschistus heros* (F.) stink bugs insects. These nanosensors can be incorporated into monitoring devices deployed in agricultural fields or indoor environments. These sensors can provide early warning systems, allowing farmers to take timely action and prevent pest infestations.

A silicon dioxide-based microelectro-mechanical system (MEMS) sensor was developed by Srujana and Bhagat (2022) to specifically detect the female sex pheromones of *Helicoverpa armigera* and *Bactrocera oleae* pests. The resulting products were user-friendly, economical, reusable, and environmentally friendly. These systems offer valuable assistance to farmers by enabling early pest detection and facilitating proactive crop protection measures. Consequently, they help to overcome the decrease in food production.

Targeted Delivery Systems: Targeted delivery approach of nanopesticide improves the efficiency and effectiveness of pest control measures. This is achieved by nanoencapsulation, size and surface effects, controlled release, stimulus- responsive systems and carrier systems. Nanoencapsulation technique involves the coating of individual solid or liquid core particles with a continuous polymeric film, allowing the pesticide to be released selectively in specific environments, such as specific pH levels (e.g. in the stomach or inside a cell), particular temperatures, moisture conditions, external ultrasound frequencies, or upon exposure to specific compounds (Urkude, 2019). The insecticidal effectiveness of acetamiprid was significantly enhanced through the nanoencapsulation technique using aluminum (Al) and polyethylene glycol (PEG). This resulted in improved lethal and sublethal toxicity towards pests (Ebadollahi *et al*., 2022). Nanoparticles have a high surface-to-volume ratio, because of which activity level and diffusion of nanoparticles are heightened. Their small size allows for effective coverage on the surface of pests. This characteristic facilitates superior performance compared to conventional pesticides (Jasrotia *et al*., 2022). Nanoparticles can be designed to respond to specific environmental cues or stimuli associated with pests. For example, pH-responsive nanoparticles can release the active ingredient when exposed to the acidic environment of a pest's digestive system. λ-cyhalothrin nanopesticides with pH-responsive properties was developed by Hou *et al.* (2023) for efficient pest control targeting *Harmonia axyridis*. This ensures that the pesticide is selectively released at the target site, minimizing exposure to non-target organisms.

Nanotechnology allows for the development of controlled release systems, where nanoparticles release the active ingredient in a controlled and sustained manner. This approach ensures a prolonged effect of the pesticide, reducing the need for frequent applications and optimizing its utilization. Nanoparticles can serve as carriers for pesticides, facilitating their targeted delivery to pests. The nanoparticles can be functionalized with specific ligands or targeting agents that bind selectively to receptors on pests' surfaces (Yoo *et al*., 2019). This enhances the uptake of the pesticide by pests while reducing exposure to non-target organisms.

Nanotechnology can improve the delivery and efficacy of biopesticides, such as beneficial microorganisms or natural enemies of pests. Nanoparticles can protect and deliver these biocontrol agents to pests, enhancing their stability, viability, and targeted action. Nanotechnology offers potential for enhancing the effectiveness of *Bt* by reducing particle size and facilitating the delivery of *Cry* toxins (Vimala Devi *et al*., 2019). The emerging class of nanobiopesticides demonstrates advantages such as enhanced stability of active ingredients, targeted and prolonged pest control.

RNA interference (RNAi). Multiple studies have provided evidence of the potential application of nanoparticles to enhance RNAi in insects through oral administration, particularly in cases where insects are typically unresponsive to RNAi (Nitnavare, 2021). Nanotechnology has been utilized in RNA interference (RNAi) for pest management, offering a promising approach to specifically target and control pests through the regulation of gene expression. Nanotechnology can be utilized for safe and effective RNA delivery to augment therapeutic effects (Byun *et al*., 2022). RNAi involves the silencing of specific genes in pests by introducing double-stranded RNA molecules that target and degrade the corresponding messenger RNA (mRNA). Mao *et al.* (2007) investigated the use of RNA interference (RNAi) in cotton plants to silence a specific P450 monooxygenase gene involved in the cotton bollworm's tolerance of gossypol, a toxic compound found in cotton. By reducing the expression of this gene through plant-mediated RNAi, the researchers observed decreased larval survival and growth in the cotton bollworm. The potential of RNAi-mediated crop protection by targeting specific genes in insects to disrupt vital physiological processes has been discussed by Zhang *et al.* (2017b). African malaria mosquito (*Anopheles gambiae*) larvae were targeted for gene silencing of chitin synthase genes through oral administration of chitosan/double-stranded RNA nanoparticles (Zhang *et al*., 2010). The successful outcomes of this study indicated the significant potential of utilizing nanoparticle-mediated RNAi technology for large-scale gene function screening and the development of innovative approaches for pest control. In *Spodoptera exigua*, the effectiveness of RNAi was enhanced by targeting chitinase synthase B using dsRNA incorporated with guanylated nanoparticles (Christiaens, 2018).

Nanoparticle-enhanced insecticides. Avermectin (AVM) serves a crucial role as a bactericidal and anti-parasitic agent targeting nematodes and arthropods. It has been proved that nanosilica could be a super nanocarrier to load and control the release of AVM (Pan *et al*., 2022). An efficient nano-delivery system for avermectin B1a (AVM) was developed by Yang *et al*. (2022) using a star polyamine (SPc), aiming to enhance the stomach and contact toxicity of pesticides. This nano-delivery system holds great potential for widespread applications in the agricultural sector. Zhang *et al*. (2017a) synthesized biodegradable castor oil-based polyurethanes (CO-PU) and utilized as carriers to create a novel type of AVM/CO-PU nanoemulsion using an emulsion solvent evaporation method. The AVM/CO-PU nanoemulsions exhibited enhanced foliar pesticide retention, and the photolysis rate of AVM (active ingredient) within the AVM/CO-PU nanoparticles was significantly reduced compared to that of free AVM.

Nanomaterials have been utilized to encapsulate insecticides in various forms, including nanocapsules, nanospheres, nanogels, micelles, liposomes, among others. These encapsulated formulations have demonstrated enhanced insecticidal effects and longer-lasting residual activity compared to their commercial counterparts (Graily-Moradi and Asgari Lajayer 2021).

Nanobiopesticides. Nanotechnology can be employed to develop novel biopesticides by encapsulating biocontrol agents (such as beneficial microbes or plant extracts) within nanoparticles. The application of nanotechnology in the preparation of *Bt* biopesticides can provide more efficient, stable, and environment-friendly *Bt* formulations (Pan *et al*., 2022). The fusion of biopesticides with nanomaterials made from natural matrices presents a highly promising avenue for achieving sustainability in agriculture. A recent study by Pascoli *et al*. (2020) demonstrated the encapsulation of the biopesticide neem oil within zein nanoparticles to enhance its stability and effectiveness. The findings highlight the promising prospects of utilizing these neem oil-loaded zein nanoparticles for pest management in sustainable agricultural practices. The synergistic effect between *Bacillus thuringiensis* subsp. *israelensis* (Bti) and silver nanoparticles (Ag NPs) was first reported by Thammasittirong *et al*. (2017).

Nanostructured Surfaces. Nanostructured surfaces have gained significant interest in the field of pest management due to their unique physical and chemical properties, which can repel or inhibit pests through various mechanisms. Biologically inspired micro- and nanostructured surface structures for insect repellency hold significant potential in effectively and environmentally-friendly controlling insect pests when compared to conventional toxin-based methods (Graf *et al*., 2018).

Categories of nanopesticides

Different types of nanoformulations for pesticides can be categorized based on their intended functions (Kah *et al*., 2013) including (1) formulations designed to enhance the solubility of water-insoluble active ingredients, (2) formulations aimed at controlling the release rate of active ingredients, and (3) formulations developed to achieve targeted delivery and improved chemical stability.

Nanoformulations and its types. There are several types of nanoformulated insecticides that have been developed like nanoemulsions, Nanosuspensions/nanodispersions, polymer-based nanopesticide formulations, lipid-based nanopesticide formulations, clay based nanopesticide formulations, porous silica based nanopesticide formulations, metal nanoparticles (Yadav *et al*., 2021). Nanoemulsions are thermodynamically stable oil-in-water or water-in-oil emulsions with droplet sizes in the nanometer range. They can encapsulate insecticides and improve their dispersibility, bioavailability, and efficacy. This formulation is strongly recommended for commercial use because of their favorable chemical properties and straightforward preparation methods (Tomlin, 2009). Nevertheless, these particular nanoemulsions also exhibit drawbacks, including their expensive production cost and potential phytotoxicity arising from the need for a significant amount of surfactant and limited incorporation into micelles (Katagi, 2008). Nanosuspensions, also known as nanodispersions, refer to pesticide formulations in which the active ingredients, such as crystalline or amorphous solid nanoparticles, are dispersed within a liquid medium (Kah *et al*., 2013). In polymer-based delivery system, the dispersion of active ingredients in aqueous media, provides a protective reservoir cover, and enables controlled release of the pesticides. Yadav *et al*. (2021) highlighted that the gradual release of active ingredients is influenced by several factors, including the degradation properties of the nanocarrier, the bonding between the active ingredients and the carrier, as well as external factors like weather conditions. Lipid-based nanopesticide formulations have been recognized as highly efficient nanocarriers for the controlled release of active ingredients, owing to their unique properties. These properties include physiochemical storage stability, environmental safety, high loading capacity, and a target-oriented smart release system (Zheng *et al*., 2013). Nanoclays, also known as clay-based nanoformulations, consist of thin sheets of silicate materials, specifically montmorillonite clays, which are frequently found in volcanic ash. These sheets have a thickness of approximately 1 nm and a width ranging from 70 to 150 nm (Saba *et al.*, 2016).

Silica-based nanoformulations, although recently introduced in the agricultural sector, have already gained significant popularity in the biomedical field due to their cost-effective and straightforward commercial production. These nanoformulations serve as highly efficient delivery systems, possessing specific surface properties, porosity, biocompatibility, increased loading capacity, and enhanced safety for the ecosystem (Liu *et al*., 2014). Besides there are metal nanoparticles which exhibit exceptional characteristics such as a remarkably high surface-to-volume ratio, substantial pore volumes, adaptable pore size, effective surface properties, and elevated thermal stability when compared to traditional formulations and microparticles, as examined by Vellingiri *et al*. in 2017.

Mode of action of nanopesticide. Benelli (2018) in his paper described about the mode of action of nanoparticles against insect. He reported that silver and graphene oxide nanoparticles have notable effects on the antioxidant and detoxifying enzymes in insects, resulting in oxidative stress and cellular demise. In addition, silver nanoparticles decreases the activity of acetylcholinesterase, an enzyme that breaks down acetylcholine while polystyrene nanoparticles inhibits CYP450 isoenzymes. Gold nanoparticles function as trypsin inhibitors and disrupt the development and reproductive processes. Metal nanoparticles can attach to sulfur and phosphorus in proteins and nucleic acids, respectively, leading to reduced membrane permeability, denaturation of organelles and enzymes, and eventual cell death. Furthermore, silver nanoparticles upregulate and downregulate essential insect genes, hampering protein synthesis and gonadotropin release, thereby causing developmental impairments and reproductive dysfunction. The toxicity of silicon dioxide and aluminum oxide nanoparticles is attributed to their attachment to the insect cuticle, followed by the physico-sorption of waxes and lipids, leading to dehydration of the insects. Charged nanostructured alumina particles adhere to the cuticle of insects through triboelectric forces, leading to the absorption of their wax layer through surface area phenomena (Stadler *et al*., 2017). As a consequence, insect dehydration occurs.

Advantages of nanopesticides compared to conventional pesticides

Nanopesticides have shown more advantages over conventional pesticides in terms of high adsorption, reduced volatilization, improved tissue permeation, controlled release, etc (Kannan *et al*., 2023). Nanopesticide formulations exhibit a high degree of target specificity (Rajna *et al.*, 2019). Targeted delivery and controlled release of nanopesticides offer the potential to enhance pesticide utilization while minimizing residue and pollution. Nano-microcapsule formulations, for instance, provide slow release and protective properties by utilizing high-polymer materials that are light-sensitive, thermo-sensitive, humidity-sensitive, enzyme-sensitive, or responsive to soil pH. These advanced delivery systems enable efficient and precise pesticide delivery, improving their effectiveness and reducing environmental impact. Nanopesticide formulations improves the adhesion of droplets to the plant surface, thereby reducing drift losses. This improved adhesion promotes better dispersion and enhances the bioactivity of the active ingredients (*a.i.*) present in the pesticide molecules. Nanopesticides represent an exceptional approach to establishing an eco-friendly and sustainable agriculture system. By reducing overall chemical usage, nanopesticides help minimize environmental impact. Moreover, they contribute to a decrease in toxic residues, promoting safer agricultural practices. Furthermore, nanopesticides enhance overall crop protection, ensuring improved yield and quality. These innovative formulations have addressed the challenges of cost reduction and pesticide volume reduction, while simultaneously improving precision, crop yield, and biodegradability. Various nanomaterials have been evaluated and have demonstrated significant potential in the development of novel pesticide formulations.

Safety considerations and regulatory aspects of nanopesticides

It is crucial to evaluate the fate and behavior of nanopesticides throughout and following their application to the environment to ascertain their potential consequences on ecosystems. A significant environmental risk associated with nanopesticides pertains to the biochemical responses exhibited by organisms. Further, phytotoxicity effects of nanoparticles on different plant systems have also been reported. The potential phytotoxicity of silver nanoparticles on tobacco *(Nicotiana tabacum*) plants was documented by Cvjetko *et al*. (2018). For instance, when spinach plants were exposed to $Cu(OH)_2$ nanopesticides or conventional $CuSO_4$, notable alterations in metabolite profiles were observed (Zhao *et al*., 2017). Specifically, nitrogen metabolism disruption was particularly evident with nanopesticide exposure. These metabolic disturbances pose substantial physiological challenges for organisms. In comparison to conventional $CuSO_4$ and $Cu(OH)_2$ pesticides, both in pure AI and commercial formulation, nanopesticides exhibited a significant reduction in the degradation rate of thiacloprid, a highly problematic insecticide (Li *et al*, 2019). This prolonged persistence of thiacloprid in soil through the use of nanopesticides has the potential to elevate the risk to non-target organisms.

Challenges in commercialization of nanopesticides

The commercialization of nanopesticides faces several challenges that need to be addressed for widespread adoption. Firstly, regulatory frameworks and guidelines for the assessment and approval of nanopesticides need to be established to ensure their safety and efficacy. This requires comprehensive risk assessments and standardized testing protocols specific to nanomaterials. Additionally, the scalability of nanopesticide production and the cost-effectiveness of manufacturing processes need to be optimized to make them economically viable for large-scale agricultural applications. Another challenge is the potential environmental impact of nanopesticides. Studies are needed to understand their fate, behavior, and potential accumulation in ecosystems to ensure that their use does not harm non-target organisms or disrupt ecological balance. Furthermore, the long-term effects of nanopesticides on soil health and biodiversity should be thoroughly investigated.

Public perception and acceptance of nanopesticides also pose challenges. Public awareness and understanding of nanotechnology in agriculture need to be improved, along with effective communication of the benefits and safety measures associated with nanopesticides.

Lastly, there is a need for collaboration and knowledge-sharing among researchers, policymakers, industry stakeholders, and farmers to foster innovation, address challenges, and develop sustainable strategies for the commercialization of nanopesticides. Overall, addressing these challenges will contribute to the successful commercialization of nanopesticides and their integration into modern pest management practices.

Additional areas where nanotechnology is being explored for applications in agriculture

Soil remediation. Nanomaterials can aid in soil remediation by efficiently removing pollutants, heavy metals, and contaminants from the soil. Nanotechnology has found extensive applications in soil remediation, effectively removing contaminants through various nanomaterials such as carbon nanomaterials, Iron (III) oxide (Fe_3O_4), Titanium oxide (TiO_2), Zinc oxide (ZnO), nanoscale zero-valent iron (nZVI), and nanocomposites (Fajardo *et al*., 2012) . Notably, nZVI has emerged as the predominant nanoparticle choice due to its exceptional efficiency in eliminating heavy metal pollutants, including toxic metals, chlorinated organic compounds, and inorganic compounds. This efficiency results in the transformation of these contaminants into less harmful compounds, showcasing the remarkable potential of nZVI in soil remediation.

Water management. Nanotechnology offers solutions for water management in agriculture. Nanosensors can monitor soil moisture levels, allowing for precise irrigation and reducing water wastage (Umasankareswari *et al.*, 2022). Additionally, nanomembranes can help in water purification, removing contaminants and pathogens from irrigation water (Khraisheh *et al*., 2021).

Crop protection. Besides insect pest control, nanotechnology can assist in protecting crops from diseases and pathogens. Nanoparticles can carry antifungal or antibacterial agents to target and control plant diseases more effectively. They can also enhance the efficacy of fungicides and pesticides. A study by Shojaei *et al*. (2016) introduced nanobiosensors utilizing cadmium telluride quantum dots (CdTe-QDs) for the detection of citrus tristeza virus (CTV). These nanobiosensors employed the fluorescence emission of CdTe-QDs, which were linked to antibodies specific to the coat protein (CTV-CP) of CTV. The researchers explored two distinct and highly sensitive approaches for rapid detection of CTV-infected plants: fluorescence resonance energy transfer (FRET) biosensors and non-FRET-based biosensors.

Pesticide detection. A newly emerging technique known as nanoparticle-assisted pesticide detection is rapidly gaining recognition. Nanoparticles possess exceptional versatility in terms of stability, compatibility, and sensitivity.Various categories of nanoparticles, including metal nanoparticles, bimetallic nanoparticles, and metal oxide nanoparticles, as well as nanotubes such as carbon nanotubes and halloysite nanotubes, have been employed in the detection, degradation, and elimination of pesticides (Rawtani *et al*., 2018).The distinct optical properties exhibited by silver nanoparticles (AgNPs) of different sizes have proven instrumental in the detection of numerous pesticides.

Post-harvest management. Nanotechnology offers solutions for post-harvest management, such as nanocoatings and nanosensors. Nanocoatings can extend the shelf life of fruits and vegetables by preventing moisture loss and inhibiting microbial growth. Emamifar and Bavaisi (2020) formulated a bio-nanocomposite coating using sodium alginate and nano-ZnO, which they subsequently applied to strawberries. Their findings revealed that the inclusion of nano-ZnO in the coating substantially enhanced the moisture barrier properties of the films, resulting in reduced weight loss of the strawberries. At the conclusion of the 20-day storage period, the coated fruits exhibited lower weight loss compared to the uncoated ones.

Resende *et al*. (2018) demonstrated that the application of a chitosan/cellulose nanofibril (CNF) coating has several beneficial effects on strawberries. Firstly, the coating significantly reduces the diffusion of oxygen, which in turn decreases respiration rates. Additionally, the coating effectively delays the oxidation of strawberries through the reaction with ascorbic acid. These findings suggest that the chitosan/cellulose nanofibril coating helps to extend the shelf life of strawberries by minimizing oxidative processes.

In their study, Chi *et al*. (2019) demonstrated that the integration of nano-silver (nano-Ag) and nano-titanium dioxide (nano-TiO2) in a polylactic acid (PLA) nanocomposite film is highly effective in reducing the loss of firmness in stored mangoes. The nanocomposite film was able to maintain the desired texture and firmness of the mangoes throughout the entire storage period, indicating its potential for extending the shelf life of mangoes.

CONCLUSION

The use of nanopesticides presents both benefits and potential concerns. Nanotechnology offers promising opportunities to enhance the efficiency and effectiveness of pesticide applications in agriculture and pest control. Nanopesticides have the potential to improve targeted delivery, reduce environmental impact, increase crop yields, and minimize health risks to humans and non-target organisms. However, it is essential to address the potential concerns associated with nanopesticides. The long-term environmental impacts of nanoparticles and their potential accumulation in soil and water systems need thorough investigation. The effects on non-target organisms, including beneficial insects, soil microorganisms, and aquatic life, require comprehensive assessment to ensure ecosystem health and biodiversity preservation. Another important consideration is the potential human health risks associated with exposure to nanoparticles, both during the manufacturing process and after application. Extensive research on the toxicity, bioavailability, and fate of nanopesticides is necessary to ensure their safe use. Regulatory frameworks should be established to assess the risks and benefits of nanopesticides and ensure their responsible development and deployment. Strict monitoring, labeling requirements, and adherence to safety guidelines are essential to protect human health and the environment. In summary, while nanopesticides hold great promise for improving agricultural practices and reducing the negative impacts of conventional pesticides, it is crucial to proceed with caution. Continued research, risk assessment, and regulatory oversight are necessary to maximize the benefits of nanopesticides while minimizing their potential adverse effects.

FUTURE SCOPE

The future of nanoformulations holds great promise in revolutionizing various fields, including agriculture, medicine, environmental remediation, and more. Nanoformulations offer unparalleled opportunities for targeted and controlled delivery of active ingredients, resulting in improved efficacy, reduced side effects, and enhanced sustainability. In agriculture, nanoformulations can revolutionize pest and disease management by enabling precise and efficient delivery of pesticides and bioactive compounds to target pests while minimizing off-target effects. They can also enhance nutrient delivery, crop protection, and stress tolerance, leading to increased yields and resource efficiency. Furthermore, the integration of nanosensors and nanodevices in precision farming can enable real-time monitoring of crop health, environmental conditions, and resource utilization, facilitating data-driven decision-making for optimal agricultural practices. While challenges remain, such as safety, regulatory frameworks, and potential environmental impacts, continued research and development efforts are poised to unlock the full potential of nanoformulations, shaping a more sustainable and efficient future across various sectors.

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