APPLICATIONS OF NANOTECHNOLOGY IN PEST MANAGEMENT OF HORTICULTURAL CROPS

Abstract

Pest infestations can exert a substantial influence on both the quantity and quality of horticultural produce. The consumption of leaves stems, and fruits by these organisms can decrease crop yield and quality, thus causing direct harm to agricultural production. The prevailing method employed for protecting horticultural crops entails the application of agricultural chemicals, including fungicides, insecticides, and herbicides. However, the prominent issues associated with these agrochemicals include heightened usage, enhanced pest resistance, and non-specific toxicity. Certain limitations exist to using traditional pesticides, which pose a risk to human well-being and the environment's safety. Therefore, utilizing a pest control strategy possessing unique attributes such as ease of use, intelligent functionality, high effectiveness, compatibility with living organisms, ability to degrade naturally, and minimal environmental impact could present a promising agricultural solution. Nanotechnology is a field of science, engineering, and technology that deals with phenomena and applications occurring at the nanoscale, typically ranging from 1 to 100 nanometers. It has demonstrated significant advancements in various scientific disciplines such as chemistry, physics, medicine, materials science, aeronautical engineering, pharmaceuticals, agriculture, food science, and horticulture. The scientific community has shown considerable interest in nanoparticles because they can be intermediaries between bulk substances and atomic or molecular structures. Nanomaterial engineering plays a crucial role in developing technologically advanced agricultural sectors by providing increased specific surface area, which is essential for the sustainable advancement of agricultural systems. This

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book chapter mainly focuses on exploiting nanotechnology in pest management of horticultural crops, nanoformulations for pest control, recent innovations in nanopesticides, risks, and regulations associated with using nanopesticides in crops.

Keywords: Pest Management, Horticultural crops, Nanotechnology, herbicides, fertilizers

I. INTRODUCTION

The term 'nanotechnology' is derived from the Greek word "nano," which translates to "dwarf." Nanotechnology is the science, engineering, and technology field that deals with phenomena and applications occurring at the nanoscale, typically ranging from 1 to 100 nanometers[74,73,78]. Nanotechnology is a developing technological field with a historical lineage spanning over two millennia [70]. “Nanotechnology” has significantly advanced in various scientific disciplines, such as chemistry, physics, medicine, materials science, aeronautical engineering, pharmaceuticals, agriculture, food science, and horticulture[37]. In response to the growing complexities associated with sustainable production and food security, notable progress has been achieved in the agricultural domain through substantial technological advancements and innovations in recent times [18, 82].Continuous agricultural innovations are crucial in addressing the escalating global food demand from a rapidly growing population. These innovations rely on both natural and synthetic resources. Nanotechnology holds significant promise for addressing various challenges associated with agriculture. The scientific community has shown considerable interest in nanoparticles because they can be intermediaries between bulk substances and atomic or molecular structures. In the past twenty years, a substantial body of research has been conducted on nanotechnology, focusing on its diverse applications within the agricultural industry [89,61,48]. These substances include nanopesticides, herbicides, fertilizers, and nanosensors (Fig.1).

Significant growth has occurred in using nanotechnology in plant protection products, which can increase crop yield. In addition, the rapid adaptation of plants to the persistent effects of climate change, such as intense temperatures, limited water supplies, salinity, alkaline conditions, and environmental contamination by toxic metals, is a significant concern for agricultural productivity [64]. It is crucial to discover solutions to these problems without jeopardizing fragile ecosystems. In addition, using nanosensors and developing nanosensors in precision agriculture has significantly improved the capacity to evaluate and monitor various aspects of crop development, soil health, diseases, the application of agricultural chemicals, and environmental contaminants. These developments have considerably enhanced human governance in soil and plant health, quality control, and safety assurance, promoting sustainable agriculture and environmental systems[89]. “Nanomaterial” engineering plays a crucial role in developing technologically advanced agricultural sectors by providing an increased specific surface area, which is essential for the sustainable development of agricultural systems [25, 33].Therefore, nanotechnology has the potential to not only reduce uncertainty but also integrate management approaches for crop production as a viable alternative to traditional methods. Agro-nanotechnology innovations frequently provide immediate technological solutions to the challenges encountered in contemporary industrial agriculture. This book chapter mainly focuses on exploiting nanotechnology in pest management of horticultural crops, nanoformulations for pest control, recent innovations in nanopesticides, risks, and regulations associated with using nanopesticides in crops (Figure 1).

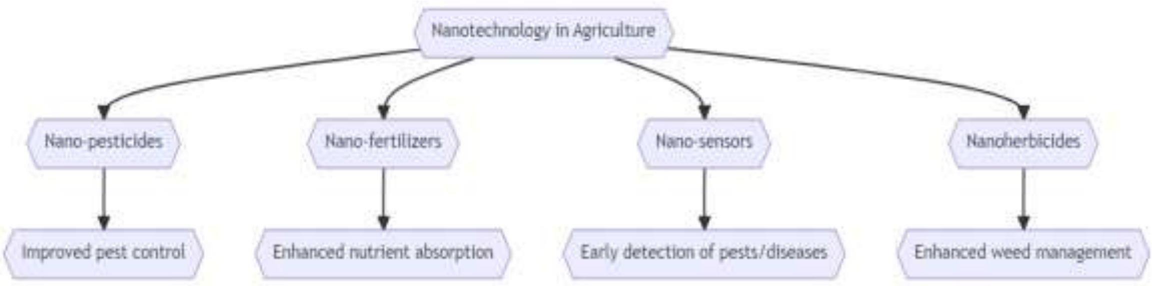

Figure 1: Potential agricultural applications of nanotechnology

II. NEED FOR PEST MANAGEMENT IN HORTICULTURAL CROPS

Pest infestations can exert a substantial influence on both the quantity and quality of horticultural produce. The consumption of leaves stems, and fruits by these organisms can decrease crop yield and quality, thus causing direct harm to agricultural production. Pests can transmit disease to crops, exacerbating crop yield and quality decline. Furthermore, it should be noted that pests have the potential to inflict indirect harm upon crops through the impairment of pollination efficacy and the heightened susceptibility to fungal infections [10,17].The potential consequences of pests on horticultural crops can be substantial. A study conducted in Jammu and Kashmir, India, revealed that the COVID-19 pandemic has caused significant disruptions in the supplychain of major horticultural crops.

Consequently, this disruption has led to an upsurge in pests and weeds within farmers' fields. As a result, it is anticipated that both the quantity and quality of horticultural crops will be adversely affected [23]. Di *et al.* [17] conducted a study that revealed that implementing anaerobic soil disinfestation can be a viable approach for managing soil-borne pests in horticultural crops, leading to enhanced crop yield and quality. Nevertheless, the influence of pests on horticultural crops can exhibit variability contingent upon the specific pest species, the cultivated crop, and the prevailing environmental circumstances.The predominant approach to safeguarding horticultural crops involves the utilization of agrochemicals, such as pesticides, fungicides, and herbicides. Pesticides play a crucial role in mitigating ecological catastrophes by enhancing the output in agriculture and ensuring the consistent growth of crop plants. As per the study conducted by the Food and Agriculture Organization (FAO), pesticide use effectively controls pathogens and pestsand has restored approximately 30% of global crop production. Agrochemicals are the foundation for safeguarding crops against biological threats, significantly contributing to food security.

Nevertheless, the prominent issues associated with these agrochemicals include heightened usage, enhanced pest resistance, and non-specific toxicity. Certain limitations exist regarding traditional pesticides, which pose a risk to human well-being and the environment's safety [86]. Therefore, using a pesticide possessing unique attributes such as ease of use, intelligent functionality, high effectiveness, compatibility with living organisms, ability to degrade naturally, and minimal environmental impact could present a promising agricultural solution. Pesticides that are primarily composed of active ingredients (AIs) and have been reformulated at the nanoscale to improve their performance and efficacy are commonly referred to as "nanopesticides" [42, 43, 44].

In recent studies, scholars have been investigating nanopesticides that exhibit enhanced properties, including but not limited to temporary degradability, increased soluble nature, improved thermal resistance, and controlled release [49]. Nanomaterials are employed in formulating nanopesticides, serving as active components or additives to function as crop protectants [51]. According to Deka *et al*. [16] and related sources, nano pesticides are expected to address the constraints associated with current approaches by offering economical, innovative formulations, mitigating pest resistance, and exhibiting targeted efficacy against pests while minimizing harm to non-target organisms. The benefits of nanotechnology pesticide formulations have been extensively documented in the literature [90, 36]. These advantages include enhanced stability of the nanoformulation, reduced volatility, removal of hazardous organic solvents, controlled release of active ingredients, increased bioavailability, ultraviolet (UV) protection, increased mobility, increased insecticidal activity, reduced residual effects, and minimized environmental runoff.According to Vasseghian *et al.* [88], using nanoformulations in pesticides offers notable effectiveness and reduced usage while demonstrating efficiency in generating hydrophobic insecticides with enhanced solubility.

III. NANOTECHNOLOGY-BASED METHODS OF PEST MANAGEMENT

Nanotechnology-based pest management techniques are gaining popularity due to their potential to enhance the stability and efficacy of botanical insecticides. The encapsulation of essential oils (EOs) into stable nanoformulations, such as nanoemulsions (NEs), has shown promise in pest management [8]. *Carlina acaulis* root EO has been proposed as a promising component for a new generation of botanical insecticides, and a highly stable *C. acaulis*-based NE capable of encapsulating 6% of *C. acaulis* EO has been developed [8]. In addition, zein nanoparticles containing botanical compounds have been developed that are responsive to proteolytic enzymes present in the insects' guts, and these formulations showed stability over time and were not phytotoxic to plants [91].

However, commercializing novel botanical insecticides and expanding the market for existing botanicals have lagged significantly behind the academic interest in natural plant products with insecticidal properties [93]. Insecticides based on pyrethrum and neem (azadirachtin) continue to lead this class of pesticides, but their increased global presence is primarily due to their introduction into new jurisdictions [93].

Nanotechnology-based pest management methods can potentially improve the stability and efficacy of botanical insecticides. However, more research is needed to commercialize new botanical insecticides and expand the market for existing botanicals [93].

IV. NANOPESTICIDE FORMULATIONS

Nanotechnology has contributed to developing diverse nanoformulationswith practical plant protection utility. The categories above encompass nanoscale formulations of insecticides, herbicides, fungicides, and nematicides.Nanopesticides are developed with specific formulations that enhance their solubility, facilitate the slow release of active ingredients, and prevent degradation, among other intended purposes. To achieve these, modifications have been implemented in the chemical composition of carrier molecules, forming and classifying formulations based on organic polymers, lipids, nanosized metals and metal oxides, and clay-based nanomaterials, among other variations. This chapter provides an analysis of various notable nanoformulations(Figure 2).

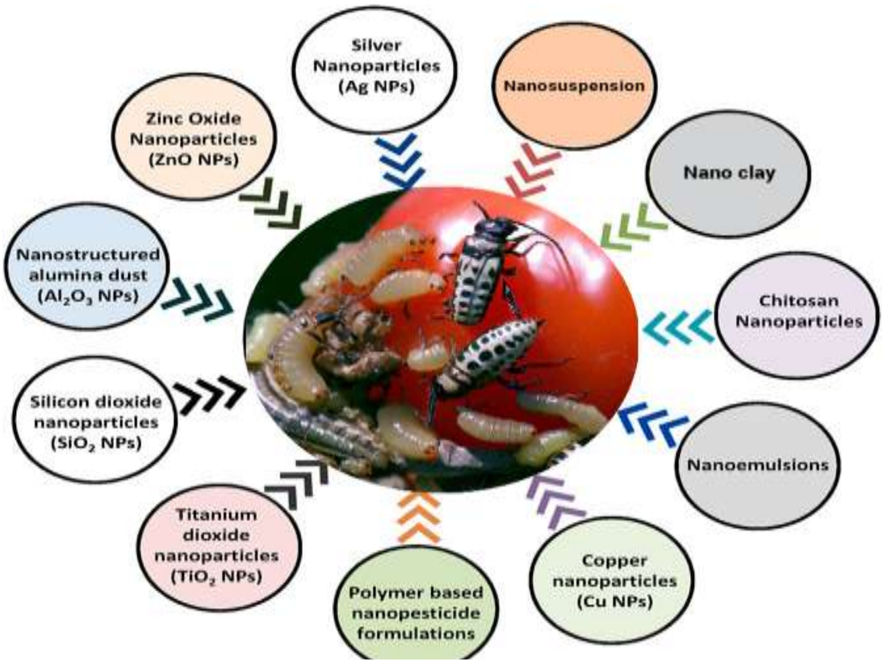

Figure 2: Types of nanoformulations

1. **Nanoemulsions:** Nanoemulsions are colloidal dispersions that are isotropic and metastable. These dispersions are composed of two liquids that are not soluble in each other and are stabilized by a surfactant that has both hydrophilic and hydrophobic properties. The droplet size of these nanoemulsions is approximately 100 nm [30]. The substances called emulsions consist of minute droplets at the nanoscale dispersed within a separate liquid incapable of mixing with them. These emulsions possess distinct characteristics that set them apart from traditional ones, rendering them appropriate for encapsulating, transporting, and formulating bioactive components in various domains such as pharmaceuticals, food, and agriculture [71]. Nanoemulsions have been identified as a potential tool for pest management in horticultural crops. These nano pesticides contain carrier molecules or active ingredients reduced to nano size [32, 69].Nanoemulsions can be categorized into two groups based on morphology [76]. The first category is composed of:

   - **Simple Nanoemulsions:** A single dispersed phase and a dispersion medium characterize simple nanoemulsions. Oil-in-water (O/W) and water-in-oil nanoemulsions (W/O) are the two nanoemulsions. In the context of O/W nanoemulsions, oil particles are dispersed throughout the continuous aqueous phase. Neutral O/W nanoemulsions, cationic O/W nanoemulsions, and anionic O/W nanoemulsions are the three varieties of oil-in-water nanoemulsions. The dispersion of water particles characterizes water-in-oil (W/O) nanoemulsions within a continuous oil phase [15].

   - **Multiple Nanoemulsions:** Multiple nanoemulsions fall into two categories: oil-in-water-in-oil (O/W/O) and water-in-oil-in-water (W/O/W) nanoemulsions. The O/W/O emulsion system is characterized by water droplets encapsulating oil droplets dispersed within an oil phase. The W/O/W emulsions consist of oil droplets encapsulating water droplets disseminated in an aqueous phase [54].Commonly, an oil-in-water (O/W) emulsion is classified as a nanoemulsion, wherein the active ingredient of the chemical is distributed in the form of nanoscale particles within a water medium. At the same time, surfactant molecules are localized at the interface between the pesticide and water. Nanoemulsions are categorized based on the composition and characteristics of surfactants, resulting in two distinct classifications: thermodynamically stable and kinetically stable. A thermodynamically stable nanoemulsion is formed when a pesticide exhibits partial solubility in the aqueous phaseand undergoes spontaneous emulsification upon combining surfactant, pesticide, and water components. The initial formation of a biphasic system arises from the insoluble nature of the active ingredient in both the pesticide and surfactant compounds. Subsequently, continuous shearing forces cause the mixture to homogenize, resulting in the dispersion of pesticide droplets in the nanoemulsion. This dispersion remains stable over a prolonged duration, indicating kinetic stability [69].Using Tween 20 as the surfactant, a nanoemulsion of neem oil dispersed in water has been developed for insect control. Due to their ability to effectively solubilize hydrophobic compounds with low water solubility, nanoemulsions have attracted considerable interest in pesticides. Fernandes *et al*. [13] reported that insecticidal nanoemulsions could be synthesized by incorporating norcantharidin (NCTD), a demethylated derivative of cantharidin, an ethanolic unrefined extract derived from the fruits of *Manilkara subsericea*, and its triterpenes. These nanoemulsions were effective against *Plutella xylostella* and *Dysdercus peruvius*, respectively.

2. **Nanosuspension:** The entities in question are colloidal dispersions at the sub-micron scale, consisting of nanosized drug particles that are stabilized by surfactants. These dispersions are commonly referred to as nano-disperse, as described by Jacob *et al*. [65]. In the context of nanodispersions, it has been observed that surfactant molecules become localized at the surface of particles. These molecules have polar segments that extend into the surrounding aqueous solution, while their non-polar segments interact with the solid pesticide. This phenomenon has been documented by Hayles *et al*. [32] and Rajna *et al*. [69]. The present study investigates aqueous dispersions containing nano-permethrin, novaluron, and β-cypermethrin.

3. **Polymer-Based Nanoparticles:** Polymer-based nanoparticles are commonly employed as pesticide carriers to achieve controlled and sustained release of active ingredients at the desired site. Additionally, these nanoparticles can improve dispersion in water-based environments and serve as protective reservoirs. This category encompasses nanomaterials, including nano-encapsulation, nanospheres, nano-gels, and nanofibers [1].

4. **Nanoencapsulation:** Nanoencapsulation is a method to encapsulate substances in tiny dimensions within the nanoscale spectrum. Nuruzzaman *et al*. [49] conducted the study. "Nanoencapsulation" is a technique employed in pest management to encapsulate pesticides, fungicides, and herbicides. This encapsulation aims to achieve controlled release and targeted delivery of these agrochemicals, essential for effective disease control and improved growth of diverse plants and crops [55, 20]. The active ingredient, which may consist of insecticides, is enclosed within a synthetic or biological polymer in

this formulation. This encapsulation facilitates the extended and effective release of the active ingredient.

Furthermore, unlike the scenario involving larger particles, it guarantees consistent distribution and enhanced chemical assimilation within the plants. Certain essential oils possess effective insecticidal properties; however, it is important to note that they are characterized by high volatility and rapid degradation. According to Pal and Chakravarthy [68], the suitability of these essential oils for nano-encapsulation has been established.

5. **Nanospheres and Nanogels:** Nanospheres are dense, solid polymeric matrices in which the drug is either encapsulated within the core or distributed across the surface, as exemplified by Joshi *et al*. [41], who have successfully developed nanospheres consisting of bifenthrin nanoparticles stabilized by polymers. The authors of Prado-Audelo *et al*. [60] describe the preparation of nanospheres that contain a pesticide either trapped within their interior or adsorbed onto their surface. These nanospheres have either an amorphous or crystalline polymeric network structure. The primary purpose of this network is to protect the active component from experiencing chemical and enzymatic breakdown. Nanogels are alternatively referred to as hydrogel nanoparticles. Hydrogels are generated by cross-linking polymeric particles containing hydrophilic groups, resulting in their ability to absorb significant quantities of water effectively[9]. Additionally, the individual expressed that implementing environmentally conscious practices in the management of fruit flies through the utilization of pheromones proves to be advantageous in mitigating the presence of these detrimental pests, which are known to have a negative impact on crop yield and quality.According to research conducted by Christofoli *et al*. [14], it was noted that the application of nanospheres made of poly-caprolactone and containing essential oils obtained from the leaves of *Zanthoxylum rhoifolium* demonstrated effectiveness in combating *Bemisia tabaci.*

   Additionally, the formulations have enhanced safeguarding for these crucial oils against degradation and oxidation mechanisms.The research conducted by Jasrotia *et al*. [38] demonstrated the efficacy of a nanogel derived from methyl eugenol, a pheromone, in managing *Bactrocera dorsalis*. This pest poses a significant threat to various fruits, such as guava.

6. **Electrospun Nanofibers:** The electrospinning technology has showcased its ability to expand and fulfill the requirements of industrial production, indicating its potential for scalingup [59].In recent research, scientists have been investigating the utilization of nanofibers created via electrospinning in safeguarding plants. The capacity of nanofibers to limit the development of release bursts caused by the non-uniform distribution of artificial intelligence (AI) within the polymer matrix is credited to their potential benefit over spheres or capsules [87]. “Researchers” have created electrospun nanofibers to contain (Z)-9-dodecyl acetate, a chemical component of pheromones. These nanofibers are then incorporated into a polymer matrix, controlling various lepidopteran insect pests [32, 69]. Xiang *et al*. [87] presented a similar nanofiber network made up of cellulose and nanocrystals of poly (lactic acid).In the glasshouse experiment, it was observed that the fibers containing thiamethoxam exhibited efficacy against whiteflies for nine days. The desired outcome was attained by employing only half of the suggested dosagefor the pure key components. The application of pesticides was carried out in a localized fashion by

utilizingelectrospun cellulose diacetate (CDA) nanofibers that were impregnated with Fluopyrum or Abm. The study results indicated that coating seeds with nanofibrous materials couldbe an alternative method for managing plant pathogens, specifically fungi and nematodes [6]. In a separate investigation, Gao *et al*. [27] employed the technique of electrospinning to fabricate a nanofiber complex consisting of thiram and hydroxypropyl-β-cyclodextrin (HPβCD), referred to as thiram/HPβCD-IC-NF. The primary objective of this study was to develop a highly effective delivery system for pesticides.

7. **Solid Nanoparticles as Nanopesticides**: Several types of nanoparticles (NPs) possess intrinsic antimicrobial and pesticidal properties, making them promising candidates for applications as nanocarriers. Additionally, these NPs can serve as potent pesticide agents or biopesticides. Inorganic particles, like clays, alumina, and silica, act as insect control agents by inducing physical damage and adhering to the protective outer layer of insects, leading to injury. It is implausible that insect pests will develop resistance to this method due to the physical mechanism of action[75].

Silica nanoparticles (NPs) represent a category of delivery systems characterized by their simplicity, effectiveness, and ease of use. They have gained significant popularity and are widely employed in various applications. The utilization of Silicon in enhancing plants resistance to various environmental and biological pressures has prompted the utilization of nanoparticles (SNPs) for agricultural pest management [85][32]. Silica nanoparticles ($SiO2$ NPs) have garnered significant interest within the field of nanomaterials as a potential substitute for conventional insecticides. As suggested by Ayoub *et al*, the insecticidal properties of silica nanoparticles are believed to be attributed to the mechanical action of directly abrading the insect cuticle.[31], Shoaib *et al*. [77]and Rastogi *et al*. [63].The findings of Thabet *et al*. [2] indicate that silica nanoparticles (NPs) exhibited superior efficacy in managing the cowpea aphid *Aphis craccivora* compared to two other insect pests, namely the American serpentine leafminer *Liriomyza trifolii* and the cotton leafworm *Spodoptera littoralis*. The researchers observed that aphids exhibited a rapid descent from the plants in response to the application of silica nanoparticles. The impact of low concentrations of silica nanoparticles on *L. trifolii*, an internal feeder, was found to be comparatively less pronounced when compared to A. craccivora, an external feeder. The populations of *Aphis craccivora* and *Liriomyza trifolii* exhibited increased reductions as the concentrations of silica nanoparticles (NPs) increased.

Based on the findings of Jafer and Al-Hasnawi [3], the efficacy of silver nanoparticles synthesized using green methods in eliminating *Tribolium castaneum* and *Callosobruchus maculatus* larvae is more pronounced when compared to both pure silver nanoparticles and the extract derived from *Nerium oleander* leaves. In 2017, Vadlapudi and Amanchy reported on the observation of the insecticidal activity of silver nanoparticles (AgNPs) [84].These AgNPs were synthesized using leaf extracts from *Myriostachya wightiana*. The study focused on their effectiveness against *T. castaneum* and *Rhyzopertha dominica*.

The study conducted by Gutiérrez-Ramírez *et al*. [35] focused on the insecticidal properties of ZnO nanoparticles (NPs) against second-instar nymphs of *B. cockerelli*. The research was carried out in a controlled laboratory environment. Notably, concentrations between 500 and 3000 ppm demonstrated significant efficacy, resulting in mortality rates exceeding 80% after 96 hours. Under controlled laboratory conditions, the TiO2 nanoparticles exhibited a significant insecticidal impact within a 24-hour. Concentrations exceeding 100 ppm led to a mortality rate exceeding 93% when attempting to control second-instar nymphs of *B. cockerelli*. The synergistic effect of titanium dioxide (TiO2) and zinc oxide (ZnO) nanoparticles (NPs) on the death rate of *B. cockerelli* was witnessed within 48 hours. The mortality rate reached 82% when 150 and 250 parts per million (ppm) concentrations were utilized. Likewise, within 72 hours, a level of 30 ppm resulted in a mortality rate of 80%. The nanoparticles of ZnO and TiO2, individually and in combination, exhibited minimal toxicity towards second-instar nymphs of *B. cockerelli* when tested in greenhouse conditions. The mortality rate observed for the ZnO and TiO2 nanoparticles was 27% and 32%, respectively, after exposure to the highest concentrations of 3000 ppm ZnO and 500 ppm TiO2 for 96 hours.The nanoparticles (NPs) displayed a fatality rate of 23% following a duration of 96 hours when subjected to a concentration of 250 parts per million (ppm). The potential of ZnO and TiO2 nanoparticles, whether used alone or in combination, in controlling pests and serving as an alternative for pest management systems is evident from their insecticidal activity. However, further research is required in this area to understand their efficacy and applicability better. The utilization of chitosan nanoparticles has been investigated for their potential application in controlling insect pests in diverse crops.

A study was conducted to examine the insecticidal toxicity of chitosan nanoparticles that were infused with *Rosmarinus officinalis* essential oil. The target of this investigation was the adult population of *Carpophilus hemipterus*, a known pest that infests stored dates. According to Soltani *et al*. [80], the investigation revealed that chitosan nanoparticles containing rosemary oil demonstrated notable insecticidal toxicity against adult *C. hemipterus* insects found in stored dates.

Nanoclays comprise thin layers of silicate minerals, characterized by a thickness of 1 nm and a width ranging from 70 to 150 nm. The primary origin of nanoclays is montmorillonite clay, predominantly in volcanic ash. These clays undergo size reduction and surface modification processes, resulting in their biocompatibility and reduced associated hazards. Among the various types of living materials, anionic clays have emerged as the most promising. They have effectively functioned as carriers for α-naphthalene acetate, a plant growth regulator, and the controlled release of 2,4-dichlorophenoxyacetate. The cinnamate natural antibiotic, commonly employed for pest control, exhibits a notable vulnerability to rapid degradation within the soil and necessitates a substantial concentration for efficacy. It was declared that by loading it on double-layered hydroxide, low-speed liberation of the antibiotic and prolonged longevity in the soil are achieved [5]. This finding demonstrates the remarkable potential of nano-clays for the controlled and targeted release of pesticides and fungicides at a reduced rate.

V. RECENT DEVELOPMENTS USING NANOTECHNOLOGY IN PEST MANAGEMENT OF HORTICULTURAL CROPS

1. **Nanoencapsulated Entomopathogens for Pest Control:** Entomopathogens are microbes that demonstrate pathogenicity against bugs, mites, and ticks. Insect pests can be effectively managed by utilizing naturally existing microorganisms, including bacteria, fungi, nematodes, and viruses. These microorganisms can infect various insect pests, which is vital to their control. Microbial control or microbial pesticides are frequently

known as the application of entomopathogens in pest management. This method is crucial in implementing integrated pest management (IPM) tactics to address different pests**.**

- **Bacteria:** Entomopathogens include spore-producing bacteria such as *Paenibacillus spp., Bacillus spp*., and *Clostridium spp.* In addition, nonspore-forming bacteria, such as those belonging to the genera *Yersinia, Serratia, Photorhabdus, Pseudomonas*, and *Xenorhabdus,* are used for this purpose.Insects that are vulnerable to the bacteria become infected after ingesting them. *Bacillus* and *Paenibacillus* are just two of the many soil-dwelling bacteria that can cause disease in beetles, weevils, flies, moths, and butterflies.Numerous strains of *Bacillus thuringiensis,* including *BT subsp. kurstaki, Bt subsp.israelensis, Bt subsp.sphaericus,* and *Bt subsp.tenebrionis*, are used to control various insect populations. For instance, *Bacillus thuringiensis kurstaki* is known to exhibit efficacy against caterpillars, while *Bacillus thuringiensis israelensis* and *Bacillus thuringiensis sphaericus* have demonstrated effectiveness against mosquito larvae. Additionally, it has been established that *Bacillus thuringiensis tenebrionis* is effective at controlling coleopterans. *Bacillus thuringiensis* (Bt) encounters alkaline conditions in the insect intestine after ingestion, typically from pH 8 to 11. This alkaline milieu activates the poisonous protein known as delta-endotoxin. Activated delta-endotoxin then attaches to specific receptor locations in the insect's midgut, forming pores within the midgut cells. This results in impairment of osmoregulation, paralysis of the midgut, and lysis of cells. The gastrointestinal contents of the insect permeate into the body cavity, known as the hemocoel. At the same time, the blood, or hemolymph, seeps into the gut, disturbing the pH equilibrium. The introduction of bacteria into the body cavity of an insect can lead to septicemia, a severe infection, ultimately resulting in the insect's demise [72].

- **Fungi:** Spores from entomopathogenic fungi infect their insect hosts and spread infection. In optimal environmental conditions characterized by suitable temperatures and relative humidity, fungal spores initiate the germination process and subsequently penetrate the insect cuticle through a combination of enzymatic degradation and mechanical pressure, thereby gaining access to the interior of the insect body. After gaining access to the host organism, the fungi experience rapid growth, infiltrate the insect's tissues, later emerge from the deceased pest, and produce more spores. *Entomophaga maimaiga* in gypsy moths, *Entomophthora muscae* in flies, *Neozygites fresenii* in aphids, *N. floridana* in mites, and *Pandora neoaphidis* in aphids have been observed to reduce the number of insects in an area significantly. The difficulty of cultivating these meticulous fungi in synthetic media hinders their commercial viability as biopesticides. In contrast, commercially available biopesticides include various species of fungi, including *Beauveria bassiana, Isaria fumosorosea, Hirsutella thompsonii, Lecanicillium lecanii, Metarhizium acridum, M. anisopliae,* and *M. brunneum.* According to Dara *et al*. [72], fungal pathogens are ideally adapted for controlling pests with piercing and swallowing mouthparts because the spores of these pathogens do not need to be ingested.

- **Nematodes:** Entomopathogenic nematodes are soft-bodied, segmentless roundworms that are parasites of insects, either obligately or occasionally facultatively. These organisms are naturally found in soil environments and can detect their hosts by responding to stimuli such as carbon dioxide, vibration, and various chemical cues. According to Malaikozhundan *et al*. [53], using species from the families Heterorhabditidae and Steinernematidae has proved highly effective in implementing pest management programs. *Heterorhabditis* and *Steinernema* have symbiotic relationships with *Photorhabdus* and *Xenorhabdus* bacteria [24, 53]. The juvenile organism expels symbiotic bacteria from its intestinal tract into the hemocoel. The bacteria undergo rapid replication within the insect's hemolymph, ultimately leading to the infected hosts demise, typically within 24 to 48 hours. Following the demise of the host organism, nematodes persist in engaging in the consumption of host tissue, undergoing maturation, and engaging in reproductive activities. According to Malaikozhundan *et al*. [53], the offspring nematodes undergo a series of four juvenile stages before adulthood.

- **Viruses:** Like bacteria, entomopathogenic viruses require ingestion by the insect host, making them well-suited to manage pests possessing chewing mouthparts. Numerous lepidopteran pests play a significant role as hosts for baculoviruses, specifically nucleopolyhedroviruses (NPV) and granuloviruses (GV). Various inclusion bodies can be observed in these viruses, where the viral particles, also known as virions, are encapsulated. The infectious particles penetrate the core of the midgut, adipose tissue, or other cellular structures, leading to compromised tissue strength and subsequent transformation of the deceased bodies into liquid form. Infected larvae will climb higher into the plant canopy before they die, allowing the virus to spread more easily from the dead to the living. Such behavior promotes the spread of the virus, contaminating larvae that have not yet been infected. Numerous viruses that can be found on the market have been recognized, including SeMNPV (*Spodoptera exigua* multi-enveloped nucleopolyhedrovirus), HzSNVP (*Helicoverpa zea* single-enveloped nucleopolyhedrovirus), and CpGV (*Cydia pomonella* granulovirus) [53].

2. **pH-Sensitive Nano Pesticides:** Pesticides are coated onto the pH-sensitive carrier substance. There are two types of pH-sensitive nano pesticides. The ionization or deionization of monoacids typically occurs within a pH range of 4–8. During this process, protons are accepted at low pH levels, while pesticides are released at neutral and basic pH levels. The pH-responsive polymer possesses an amino group on its side chain that can accept protons in acidic conditions and release them. In a study by Patel *et al*. [56], a pH-responsive alginate nanocarrier was developed to deliver cypermethrin. Under conditions of acidic pH, there is a notable increase in ionization, leading to the interaction between an alginate polymer and calcium ions. This interaction results in enhanced cross-linkage, thereby rendering the interior of nanoparticles more hydrophobic. Consequently, the release rate of insecticide is reduced.

3. **Nano Emulsified Insecticides/Pesticides Utilizing Green and Essential Oil (EO) Components:** In recent times, there has been a significant focus on the investigation of novel and naturally occurring bioactive compounds that possess the ability to control pests or insects. Medicinal plants are valuable botanical resources for this study due to their abundance of potent natural defensive compounds and minimal unintended toxicity. Furthermore, it has been demonstrated that this phenomenon has benefited human and environmental well-being. Using nanomaterials for encapsulation serves as a strategy to address the inherent physicochemical characteristics of these substances, thereby

augmenting their effectiveness. According to Pavoni *et al*. [57], using natural plant-based nanoemulsion formulations has proven to be a viable method for achieving efficient pest control. This solution offers a sustainable and ecologically conscious alternative for effectively addressing insect pests and crop diseases, thanks to its natural biodegradability, environmentally friendly properties, and overall safety. It is a highly potent asset for developing and creating insecticides with significant efficacy. According to Campos *et al*. [19], research has indicated that using botanical insecticides positively impacts soil health and biodiversity. Nevertheless, this technology utilization is limited due to inherent issues with stability.

By creating new formulations based on botanical nano-emulsification, nanotechnology is used to standardize and stabilize natural products. This action is taken to address and resolve the issues above. Nanoemulsions derived from green essential oil (EO) have recently attracted considerable interest in the food and agriculture industries due to their remarkable insecticidal properties. EO is commonly referred to as ethereal, volatile, and aromatic oil. The Food and Drug Administration of the United States has certified a large number of these essential oils (EOs) as generally recognized as safe (GRAS) substances [4].These EOs have the potential to contribute to the management of insect pests and pathogens effectively. Plant metabolites such as monoterpenoids, sesquiterpenoids, and phenylpropanoids are commonly used to make essential oil (EO) [8]. These compounds have extensive applications in food, pharmaceuticals, and agriculture. Based on the available data, it can be observed that EO demonstrates various properties such as insecticidal, bactericidal, fungicidal, antiprotozoal, anti-inflammatory, and anticarcinogenic effects. However, it is essential to note that EO is also associated with certain limitations. Using colloidal-based manufacturing techniques has been acknowledged as a valuable strategy for tacklingvarious challenges related to essential oils (EOs). These challenges include evaporation, poor stability, dispersion, intense sensory properties, restricted longevity, and ways of administration [52]. This technique aims to enhance the potency of eOs, as highlighted by studies conducted by Echeverría *et al*. [21] and Jesser *et al*.[40]. According to de Oliveira *et al*. [92], shielding carriers can effectively encapsulate the substances, resulting in a controlled release mechanism that mitigates their rapid evaporation and degradation.

According to Benelli *et al*.[8], using essential oils (EOs) as carriers have been proven to be very successful in boosting several qualities, including stability, hydrophilicity, effectiveness, and ecological resilience, in addition to its inherent potential. In addition, it is used to keep them functioning generally from a biological standpoint [50]. An oil-in-water colloidal system is used to encapsulate semiochemicals and control their release. According to Lucia and Guzmán [46], this tool enables the monitoring of insects, trapping them, studying their mating distribution, and manipulating their behavior. The larvicidal activity of essential oil-based nanoemulsion was enhanced, as demonstrated in the study conducted by Balasubramani *et al*. [7]. Incorporating essential oils (EOs) into nanoemulsions facilitates the utilization of target-specific mechanisms and enhances the efficacy of interactions with pests. The reduction of the dosage regimen and the enhancement of efficacy are observed. Cationic emulsion and anionic pathogens in pesticides cause metabolic disruption on a cellular level in insects. The lipid membrane of the pest is a target for the nanoemulsion. Cell death and lysis occur due to the simultaneous release of active compounds and entrapped energy, which disrupts the lipid membrane.

Nanoemulsions have become an intriguing option as a pesticide agent in modern crop protection. Nenaah *et al*. (2015) conducted a study in which they nano-emulsified the essential oils of *Tagetes minuta*, *Ageratum conyzoides*, and *Achillea fragrantissima* using the high-pressure homogenization (HPH) method. The results of this study demonstrated the effectiveness of these nano-emulsified essential oils against *Callosobruchus maculates*, the cowpea beetle. Golden *et al*. [28] developed a nano-emulsified formulation of pulegone to combat the pervasive problems posed by the rice weevil (*Sitophilus oryzae* L.) and the red flour beetle (*Tribolium castaneum* Herbst). The rate of bioactivity increases by approximately 95% within five weeks. The plant known as *Tanacetum cinerariifolium*, commonly called white pyrethrum daisy, is recognized for producing pyrethrin, an environmentally friendly botanical insecticide. The insecticidal efficacy against cotton aphids, *Aphis gossypii*, on eggplants is enhanced by a biocompatible colloidal dispersion based on oil-in-water (O/W) nanoemulsion[45].

Furthermore, the application of nano-formulated pesticides has effectively eliminated non-target contaminants. The study by Ramadass and Thiagarajan (2017) found that nanoformulations of pyridyl were highly effective in controlling the cotton bollworm species *Helicoverpa armigera*. In a separate investigation, Pehlevan and Kovanc[58] employed the non-ionic surfactant Tween 20 to manage the lymph of *Cacopsylla pyri* (L.). Nano-emulsification-based formulations are highly efficient in mitigating the harmful impacts caused by insect pests, including the damage they inflict on stored products and subsequent weight loss. Choupanian and colleagues [12] discovered that applying neem oil in nanoemulsion effectively controlled *T. castaneum*, a well-known insect that causes injury to stored cereals. The compound was significantly toxic (LC50 = 9.3% v/v) to *T. castaneum*, the red flour beetle. Based on a separate investigation, it was discovered that eucalyptus oil (EO) in its nano-emulsified form exhibited significant efficacy in controlling stored cereal pests such as *Rhizopertha dominica* and *T. castaneum* [81].

VI. CONCERNS ABOUT THE USE OF NANOPESTICIDES

One of the reasons why nano pesticides are preferred over traditional pesticides is their ability to combat environmental contamination by reducing pesticide usage and mitigating losses [39,47]. On the other hand, these factors could present a novel challenge regarding increased durability and toxicity. The presence of nanodroplets with a reduced droplet size may result in premature evaporation before they reach their destination. There is a need for additional research into the effects of nanoformulations on microorganisms, plants, and other animals at various levels of the food chain. In addition, it is unknown how pesticide nanoformulations may influence soil, groundwater, and organisms that are not intended targets. The characteristics of the nanocarriers and the distribution of the active ingredient within the nanoformulation matrix regulate the discharge of active ingredients into the environment. Kah *et al*. [42] have documented the potential impact of delayed nanoparticle discharge on non-target organisms. The predominant nanocarriers utilized in nanoformulations are natural polymers, polysaccharides, or lipids, which are highly susceptible to degradation. However, there has been little focus on using non-biodegradable nanocarriers, such as metals and metal oxides [43]. Moreover, a significant proportion of synthesized nanocarriers are explicitly designed for controlled release, which may result in restricted exposure of nanoformulations to the human body [62].Traditional formulations necessitate the use of environmentally hazardous organic solvents in the production of nano pesticides.

There is a deficiency in regulations aboutnanoproducts' registration and market entry. Uniform criteria must be established to assess nanochemicals before they are registered and sold commercially. Understanding their behavior, toxicity, efficacy, physicochemical qualities, and consequences is essential to mitigate their adverse effects on humans and the environment. It is imperative to conduct research studies that compare nano pesticides with their conventional analogs across various dimensions.These studies are crucial in guiding future research endeavors to assess the environmental risks ofnano pesticides, utilizing life-cycle analysis as a framework. The development of nanoformulations, including their use, levels of incorporation into the food chain, and their possible impacts on agroecosystem conditions should be examined.These factors should be considered to assess nanomaterials' hazardous properties and risk characterization.Given their extensive utilization, the scientific community is increasingly apprehensive regarding nano pesticide formulations' potential toxicity and ecological consequences. Consequently, further examination and investigation in these domains are warranted. Hence, it is imperative to allocate additional resources toward exploring and discovering strategies to advance safer and more intelligent nanoformulations.

VII. REGULATIONS OF NANO PESTICIDES

The utilization of nanomaterials across diverse disciplines is experiencing a notable upward trajectory in contemporary society's technologically advanced landscape. Nevertheless, conducting an environmental risk assessment for nanomaterials, including nano pesticides, is imperative before their global market introduction. Before their introduction, it is crucial to thoroughly evaluate nanomaterials, including their durability, actions, and destiny in the surroundings. All regulatory and legislative bodies globally require safe utilization and accurate assessment of hazards connected with various operations. According to Singh *et al.* [79], the unique attributes of nanoparticles, including their size, surface area, and catalytic properties, necessitate the implementation of supplementary evaluation measures to establish their toxicity thresholds, surpassing conventional guidelines. Numerous domestic and global regulatory entities actively endeavorto safeguard nanomaterials' safety. For the regulation of nanoproducts, heterogeneous methodologies are used in several locations, including Asia, Africa, and Oceania. Countries use different versions of these methods [66]. “Naqvi” and Flora [67] set standards for evaluating nano-agri input goods and nano-agriproducts. These guidelines clearly define nanomaterials, categorizing them as either nanofertilizers or nano pesticides. The Scientific Advisory Panel (SAP) of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) of the United States has been discussing using nanometals and metal oxides in pesticide formulations.

In light of these discussions, the SAP has issued a recommendation emphasizing the importance of evaluating these nanomaterials' potential health and environmental hazards before commercialization [29]. In addition, it is essential to note that the regulation of plant protection products (PPPs) in Europe falls predominantly under Regulation (EC) No. 1107/2009. This regulatory framework requires prior authorization from the government before using these products [34]. The European Food Safety Authority *et al*. [22] state that (EC) No. 396/2005 is the regulatory framework governing the monitoring of food nanomaterial residues. In addition, the REACH Regulation (EC) No. 1907/2006 addresses the issue of workplace safety about these substances. This rule provides producers and importers with pertinent information about the potential risks of using nanomaterials [83,26].The Australian Pesticides and Veterinary Medicines Authority (APVMA) instituted nanomaterial release regulations. The primary objectives for research and development (R&D) efforts in countries worldwide should center on mitigating ecotoxicity associated with nano pesticides. These objectives can be achieved through the establishment of standardized testing protocols for nano pesticides, a comprehensive comprehension of the potential hazards posed by nano pesticides and their degradation byproducts, prolonging the duration of exposure in nano pesticides testing against specific organisms, and the identification of nano pesticides that fall within the regulatory purview.

VIII. CONCLUSION AND FUTURE PROSPECTS

Nanoformulations offer numerous benefits compared to conventional formulations of pesticides due to their intelligent and more precise release mechanism and heightened target specificity. The minimal dosage of pesticide employed prevents the development of resistance in pests. Controlled-release formulations correlate positively with increased crop yield and enhanced pest control compared to their commercial counterparts. The levels of pesticide residues present in seeds or soil at the time of harvest were found to be below the detectable thresholds. Nano-pesticides possess significant potential to transform contemporary agriculture by mitigating the environmental impact associated with conventional pesticide usage. The potential impact of nanotechnology applications on agricultural production is significant, as it enables enhanced scientific management and conservation measures for plant production. Nanotechnology researchers possess the capacity to make numerous valuable contributions to society by applying this technology in agricultural and food production systems. Nanotechnology offers a significantly enhanced environmental detection, sensing, and bioremediation approach.

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