Chapter

Revolutionizing Integrated Pest Management Using Nanobiotechnology: A Novel Approach to Curb Overuse of Synthetic Insecticides

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Abstract

Nanotechnology: A promising field of advanced interdisciplinary research has unlocked an extensive range of scenarios in the sectors like agriculture, electronics, pharmacy, healthcare, pest management and much more. In agriculture, the potential uses and benefits of nanotechnology are enormous. With the use of Nanotechnology, the management of insect pests through the formulations of nanomaterial-based insecticides have changed the course of Integrated Pest Management (IPM). Traditional strategies in Integrated Pest Management used in agriculture are insufficient and the application of chemical pesticides have caused adverse effects on animals, human health and the environment. With the utilization of nanotechnological approaches, the green and efficient alternatives would provide the management of insect pests without causing an impact on animals and the environment. The present study aims to focus on the management of insect pests utilizing modern nanotechnological approaches.

Keywords: insecticides, pests, IPM, nanotechnology, sustainability

1. Introduction

There has been a major spike in terms or global human population across the planet. Since global croplands are limited and to feed almost 8 billion people is a boiling issue both developed and developing nations are facing in the present times [1, 2]. Agriculture sector is a backbone for the economies of many farming dependent nations [3, 4]. However, cultivating large-scale crops and higher quantity of crop production requires time, money and energy and most importantly the care. As long as there have been farms, farmers have been battling pests. Pests, weeds and other fungal, bacterial or viral diseases are a natural result of ecological disturbance. Modern pesticides have now been available for over 60 years [5]. In the 1940's when pesticides became available, farmers gained powerful and easy to use weapons for defeating harmful organisms [6]. The new chemicals were so effective that research on ecological methods of pest control was largely abandoned. The next generation of farmers learned very little about nonchemical approaches to controlling pests. However, over the years mankind has discovered serious drawbacks to chemical pest control. A large number of insects developed resistance to pesticides and cropland weeds learned to tolerate herbicides [7]. Newer more expensive products were required to cope with the resistance and many pest control products contaminated the environment and caused unintended damage to beneficial insects including pollinators, predators and parasitoids, aquatic life, avifauna and wildlife [8–14]. The agricultural communities from different parts of the world were compelled to develop broad-based ecologically sound pest-fighting strategies. From their efforts, a series of practices emerged we now call Integrated Pest Management (IPM).

Integrated pest management is an approach to controlling pests that takes advantage of the broad variety of management practices that are available to farmers [15]. The strategies used in IPM can save both economy and crops of farmers as it offers alternatives to expensive pesticides and herbicides which most of the farmers are not able to buy. Integrated Pest Management is built on four main principles, often known as prevention, avoidance, monitoring and suppression (PAMS) approach [16]. Since it is easier to prevent pests and diseases from developing than to control them after they appear in our farm fields. In IPM, the most important aspect for controlling pests is that the pathways need to be interrupted that enables pests to reach the farm fields as it requires less energy and time. IPM is literally based on the initial pest control strategies which include:

1. Knowledge of pests (Life cycles of pests and their natural enemies).

2. Prevention strategies (Site selection, time of plantation, nutrition and hygiene).

3. Monitoring (Observation, monitoring and traps).

4. Intervention (Chemical, Mechanical and Biological control).

5. Evaluation and review

Integrated Pest Management has been Individuals initiating and utilizing the IPM strategies must be educated about each pest and the options that he is choosing for eliminating pests. The strategies initiated in the IPM must be closely monitored as methods differ for each crop and area. As pests have a higher reproducing rate in increasing temperature especially in spring and summer which is also the developing period of most of the crops. Avoiding the reproduction and development of such pests, conventional pesticide application usually synthetic pesticides take less time to eliminate pests from the farm fields. However, with the passage of time, the pests and weeds develop resistant behaviors to most of the chemical pesticides, herbicides and biopesticides as well. The large-scale utilization of chemical pesticides and low stability of biopesticides have cost us both the health of ecosystems and burden of crop losses.

Nanobiotechnology is the modern approach and can be used to overcome the large-scale utilization of synthetic pesticides. The novel nanopesticides and nanofertilizers aims at reducing the pesticide pollution which has innumerable impacts on our ecosystems, life and human health. The advancement in the field nanotechnology and the utilization of nanomaterials in the agriculture will change the course of human history and sustainable development. Nanobiotechnology in agriculture, if planned and utilized in a proper manner will lead to sustainable development (**Figure 1**).

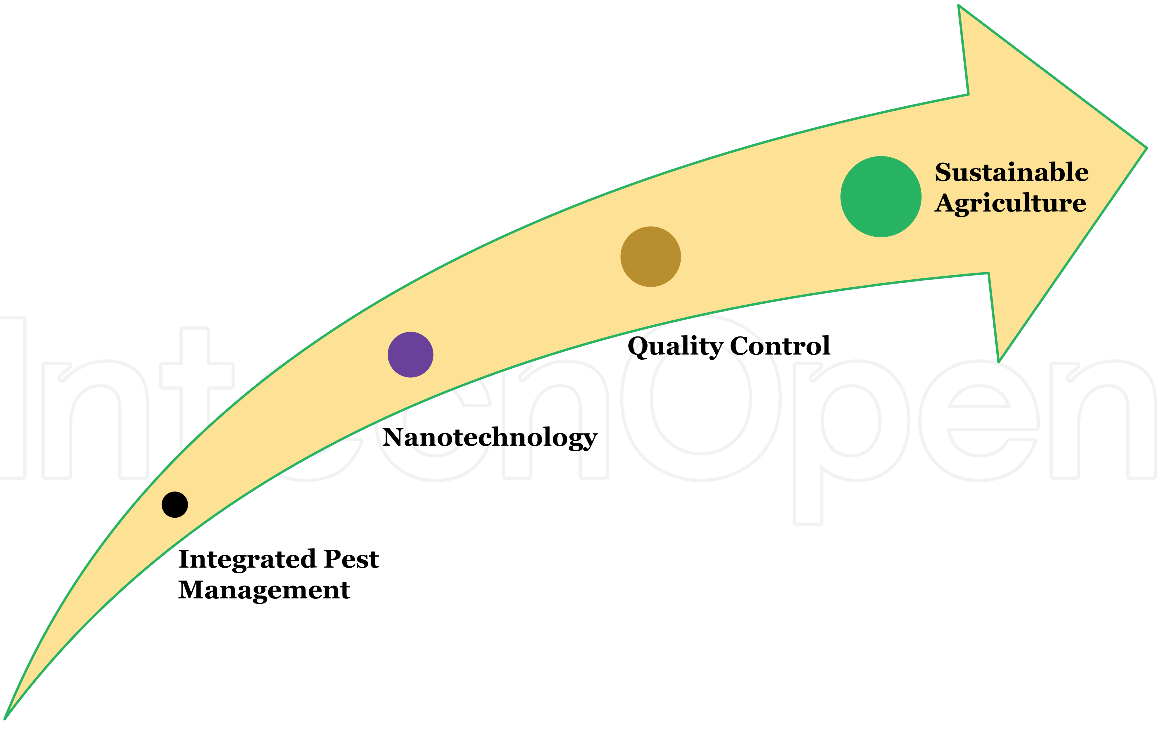

Figure 1.
Sustainable agriculture can be achieved by utilizing nanotechnology with quality control.

In this chapter we give an overview of agriculture and global food security, we also discuss about crop loss and rising global food demand, impact of synthetic pesticides on environment and finally we have comprehensively described the applications of nanobiotechnology/nanotechnology in agriculture especially in pest control.

2. Agriculture and global food security

Food security has always been a major concern for human civilizations throughout the history [17]. In 1974 World Food Summit, food security was defined as for the first time: "availability at all times of adequate world food supplies of basic foodstuffs to sustain a steady expansion of food consumption and to offset fluctuations in production and prices" [18]. From time to time the definitions have been modified. "Food security, as defined by the United Nations' Committee on World Food Security, means that all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life". Concerns regarding the global food security and production have grown in recent decades. Climate change, population growth, rising food prices, and environmental stresses will all have substantial effects on food security in the future decades. Adaptation techniques and policy responses to global change are urgently needed, including alternatives for managing water allocation, land use patterns, food trade, postharvest food processing, food prices, and food safety. Furthermore, in developing countries, changing lifestyles and diets have impacted the demand for meat and dairy products [19]. Increasing demand for the food will inevitably increase land competition, food security and availability remains one of the most pressing issues on the public agenda [20]. The agriculture sector's challenge is no longer merely to maximize output and feed 9 billion people without large increases in food prices until 2050, but also to ensure food availability, distribution, and social justice for all people.

3. Factors affecting global food security

Overpopulation, climate change, and urbanization are three worldwide concerns that have an impact on food security. Hunger and disease are most prevalent in areas of the world with the largest birth rates and population, where demand typically exceeds supply. Local ecosystems provide resources for food production, health, environmental management, and water to the people. The local ecosystem has a limited carrying capacity, and when this capacity is surpassed, the ecosystem comes under stress and starts to break down. This condition has been termed as ecosystem vulnerability [21]. Such vulnerable condition of the ecosystem can give to over-farmed soils, denuded grazing lands and dried up or contaminated wells.

Climate change is affecting various regions of the world. Climate change can affect food security and hence human health in a variety of ways. [22, 23]. One important route is through climate change affecting the amount of food produced, both directly and indirectly through implications on water availability and quality, pests and diseases, and pollination services. Another way involves altering CO_2 levels in the atmosphere, which has an impact on biomass and nutritional quality. Climate change can worsen food safety issues during transportation and storage. Limited food sources lead to nutritional deficiencies and these deficiencies can cause immune suppression and make the population more prone to illness [24]. Diseases lead to a greater demand on the body's energy reserves and necessitates the consumption of nutrients that aren't readily available. This is a cycle of hunger and disease that shortens one's life, decreases productivity, and limits one's potential.

Furthermore, due to the agricultural workforce's exposure to high temperatures, the direct effects of altering weather might have an influence on human health. There is the possibility for interactions with food availability due to changes in metabolic needs and physiological stress for persons exposed to severe temperatures; people may require more food to cope while simultaneously being unable to produce it [22]. All of these elements have the potential to affect both physical and cultural health by affecting the amount and quality of food available to people.

Food insecurity is aggravated by urbanization. Megacities, defined as cities with populations of 10 million or more, are particularly frequent in developing nations. In fact, low- and middle-income nations account for three-quarters of urban residents. The global economy has benefited from these nations' low-cost labour, which has fueled rural-to-urban migration. The majority of manufacturing jobs are in cities, and when overcrowded and depleted lands fail to provide basic economic requirements despite their ability to generate sufficient food, people migrate to these urban jobs and opportunities. Until now, rural farmers have been able to keep up with demand, but urban people' economic access to food remains a concern. The demand to feed these megacities, as well as the difficulties linked with economic food access, is enormous. This was seen in the years 2007 and 2008, when rising oil costs made food expensive for city residents all across the world [25].

Food security is not only about humans and their environment; it also involves animals, who are a key source of food for humans. As a result, under this situation, we cannot neglect infectious animal illness. Contagious animal illnesses can wipe out an animal population or drastically impair its productivity, which has an impact on food supply and access. Even if humans are not afflicted, the illness frequently has a significant impact on them. Any loss of animals means a loss of protein in the form of milk, meat, or blood, as well as a supply of labour to plow fields and deliver food to markets. Even illnesses with a low case-fatality rate but a high morbidity rate, such as foot and mouth disease, produce such severe sickness in the animal that its productivity is severely diminished. This can influence the food supply. Avian influenza, especially H5N1, decimated flocks across the Western Pacific, posing a food security issue [26]. Furthermore, zoonotic illnesses put people at danger when they ingest these animals, which happens often even when the animal is unwell. In terms of access and availability, food instability may push communities to seek alternative food sources, such as bush meat, thus exposing them to additional illnesses. This has been the case with illnesses such as sudden acute respiratory syndrome, acquired immunodeficiency syndrome (AIDS), and others [27].

Agriculture is directly or indirectly linked to the livelihood of a large percentage of the population in the developing countries. In recent years, agricultural productivity growth has slowed. Land is a limited resource, and many emerging nations are unable to expand their farmed areas [28, 29]. As a result, increasing agricultural production may be the only way to fulfill future food demand for a growing population. Because cultivable fertile land and related inputs are limited in most areas of the world, a new strategy to increasing future agricultural productivity development in most regions of the world may be intense agricultural expansion rather than widespread growth. As a result, diversification coupled with intensification of production and improving the resource utilization are important essential measures [30]. The disparity between feasible and actual yields for most crops implies a huge opportunity to boost food and agricultural output by increasing productivity [31]. According to the Food and Agriculture Organization, UN (FAO), in the developing world, around 80% of the growth in food production will have to come from increased yields and cropping intensity, with just 20% coming from arable land expansion [32]. As a result, intensification is critical not just to satisfy the growing demand for food grains, but also to reduce deforestation, environmental devastation, and global warming.

4. Global burden of crop loss and rising food demand

Crop loss is impeding efforts to achieve the Sustainable Development Goals in food security, nutrition, and livelihoods. Pests and disease may take away up to 40% of agricultural output, but the data available to confirm and illustrate trends is inadequate. The Global Burden of Crop Loss project will gather, validate, analyze, and disseminate data on the extent and causes of crop loss, with the goal of gathering enough and reliable data to enable prioritization of plant health research and policy, improving our ability to predict the impact of emerging diseases. One of the defining problems of our time is meeting rising food demand in the face of climate change and increasingly variable agricultural conditions. To ensure that adequate food is accessible for all of us for centuries to come, we will need to produce considerably more food while minimizing environmental damage. Pests and diseases are responsible for an estimated 20–40% of agricultural production loss worldwide. Losses of basic cereals (rice, wheat, maize) and tuber crops (potatoes and sweet potatoes) have a direct impact on food security and nutrition, but losses of essential commodity crops like banana and coffee have a significant impact on household incomes and national economies. Climate change also increases the threat of plant pests and diseases, impeding progress on several of the UN's Sustainable Development Goals. A big component of this will be reducing crop loss, and considerable efforts will be required to enhance pest control, particularly diseases and weeds.

Crop loss assessment research has traditionally been divided into three stages: exploratory, development, and implementation. These phases occurred at various times in agricultural research, with the goal of improving our understanding of the influence of diseases on crop output quantity and quality. The loss of biodiversity is speeding up all across the planet as this tendency is mostly driven by the global food system. The conversion of natural ecosystems for agricultural production or grazing has been the primary driver of habitat loss in the last 50 years, resulting in a reduction in biodiversity. The 'cheaper food' concept has influenced our food system over the last few decades. The goal of policies and economic systems has been to produce more food at cheaper costs. Intense agricultural production damages soils and ecosystems, reducing land productivity and forcing even more intensive food production to keep up with demand. These constraints are being exacerbated by the worldwide consumption of lower-calorie, resource-intensive foods. Food production today is largely reliant on unsustainable techniques such as monocropping and excessive tilling, as well as inputs such as fertilizer, pesticides, energy, land, and water. This has diminished the diversity of landscapes and habitats, posing a threat to or eliminating the breeding, feeding, and/or nesting of birds, animals, insects, and microbiological species, as well as pushing out many others. Our food system is a major source of global greenhouse gas emissions. Climate change is also causing habitat degradation and species extinction to spread to different places. Biodiversity loss will continue to increase until our food system is reformed. Our ability to survive will be jeopardized if ecosystems and habitats are further degraded.

By 2050, food consumption is predicted to grow by 59 to 98%. This will have a profound impact on agricultural markets. Farmers throughout the world will need to boost crop output, either by expanding the quantity of agricultural area available for crop production or by improving productivity on existing agricultural lands through fertilizer and irrigation, as well as adopting innovative technologies such as precision farming. Global demand for agricultural commodities is rising and may continue to do so for decades, fueled by a projected 2.3 billion rise in global population and higher per capita incomes through 2050 [19]. Both land clearing and more intensive use of existing croplands might help satisfy this need, but the environmental consequences and costs of these various agricultural expansion pathways remain unknown [33]. Agriculture already has significant global environmental impacts: land clearing and habitat fragmentation threaten biodiversity, land clearing, crop production, and fertilization account for about a quarter of global greenhouse gas (GHG) emissions [34], and fertilizers can harm marine, freshwater, and terrestrial ecosystems [35]. Quantitative estimates of future crop demand and how alternative production techniques affect yields and environmental factors are required to understand the future environmental consequences of global crop production and how to attain higher yields with fewer impacts. To fulfill increasing food demand while also halting and reversing environmental deterioration, significant improvements in resource-use efficiency and advances in resource conservation will be required globally. Despite certain technical advancements, crop growth has slowed substantially compared to earlier decades. The detrimental side effects of heavy usage of chemical inputs in agricultural production have become increasingly evident, raising major questions about long-term sustainability.

Agriculture, fisheries, and forestry investments, as well as research and development funding, must be increased, particularly in and for low-income nations. This is necessary to encourage the adoption of sustainable production systems and practices, such as integrated crop-livestock and aquaculture-crop systems, conservation agriculture, agroforestry, nutrition-sensitive agriculture, sustainable forest management, and sustainable fisheries management, among others. These and other types of climate smart agriculture will assist farms, ecosystems, and communities in adapting to, mitigating, and building resilience in the face of climate change.

5. Impact of synthetic insecticides on environment

Insecticides are generally chemical compounds developed for eliminating the insect pests from agricultural fields, storage warehouses, homes etc. Man has been utilizing pesticides from the time immemorial. Though, utilization of chemical pesticides brought a relief to farmers by expelling the pests from the farm lands. However, the large-scale usage of synthetic insecticides was proven to be incompatible for the environment. Impact of synthetic insecticides on various life forms and different ecosystems has been reported across different places of the world. The nations engaged in the different agricultural and allied sectors are mostly affected from it. With the rise in global population and the food requirements, there has been a parallel growth in large-scale cultivation of high yielding monocrops. Since, crop loss by the pests was controlled by the pesticides, however a long-lasting adverse impact on various life forms and natural environment end up being a major issue to be taken care of. On contrary, health of farmers has also been declined to the worst in some studies as the farmers are most exposed to the toxicity levels of synthetic insecticides. The synthetic insecticides have been proven to be most devastative on the beneficial insect diversity including pollinators such as honey bees, dipteran pollinators, predators, parasitoids and other useful insects which deliver several ecosystem services. In an agricultural field, a number of insects can be seen collecting nectar and pollinating the flowers such as bees, wasps, hoverflies, moths & butterflies and some species checking the populations of insect pests such as parasitic wasps, hornets, beetles, lacewings etc. While splashing synthetic insecticides on crops infested with pests, 15 to 40% of an estimated fraction of insecticides are scattered into the atmosphere by either volatilization or spray drift processes [36]. After spraying, the insecticides in atmospheric particulate phase will remain in the air for about 7–12 days and can thoroughly orbit many geographical locations across the globe. The orbiting of pesticides in the atmosphere can alter air quality and may add more events to the climate change [37]. The pesticide runoff from the agricultural lands into streams and lakes have a great impact in the aquatic life and water contamination. Though runoff can be the transportation of pesticides into aquatic ecosystem, the atmospheric dispersal of pesticides can travel to other places like grazing fields, human settlements potentially affecting other living organisms and human wellbeing. The impact of synthetic agro-chemicals on insect diversity has been well documented across the globe. There has been a massive decrease in insect pollinators and other beneficial class of insects from past few decades due to the large-scale utilization of insecticides and other agrochemicals [38, 39]. Alternative measures are needed to substitute the overuse of synthetic insecticides and other agrochemicals.

6. Nanotechnology and agriculture

Agriculture has traditionally been the most significant and stable sector in the economy since it generates and supplies raw materials for the food and feed industries. Due to the finite nature of natural resources and the world's growing population, agricultural expansion must be economically feasible, ecologically friendly, and efficient. This change will be critical for attaining several goals in the coming years [40–42]. Agricultural nutrient balances change considerably with economic expansion, and as a result of this assumption, the improvement of soil fertility in emerging nations is extremely important [43]. Recently, a wide range of possible uses of nanotechnology in agriculture have been proposed, prompting extensive research at both the academic and industry levels [44–46]. Indeed, the unique characteristics of nanoscale materials make them ideal candidates for the design and development of new agricultural equipment. As a result, research into nanotechnology's uses in agriculture has gained a lot of attention in recent years.

6.1 Nanopesticides

Pesticide use is common in commercial agriculture, and research and development of novel, effective, and target-specific pesticides is ongoing. As a result, each year a huge number of pesticides are spayed in the agroecosystems. Only 0.1% of pesticides sprayed reach the target pests, while the rest (99.9%) contaminates the environment [47]. This has significant repercussions for the food chain and human health. Pesticides' pervasive presence in the environment has led in the development of pesticide resistance in weeds, insects, and diseases, in addition to the impact on non-target species [48]. Biopesticides tend to decrease the harmful effects of synthetic pesticides, but their usage is limited due to their sluggish and environment-dependent pest-control efficacy. As a result, nanopesticides are critical for the successful and long-term control of many pests, and they have the potential to reduce the usage of synthetic chemicals and their related environmental hazards. To improve their efficacy, nanopesticides act differently than the conventional pesticides [49]. Nanoparticles may be transported in dissolved and colloidal phases, and this process explains why their behavior differs from that of ordinary solutes of the same particles [50]. The mobility and breakdown of active substances by soil-dwelling microbes may be aided by their solubility. Because nanoparticle-based pesticides improve the solubility of aluminum, they are also regarded to have a lower environmental effect than conventional pesticides [51].

Nanoparticles have been shown to have antimicrobial action against bacterial, fungal, and viral infections. Silver [52], copper [53], and aluminum are significant inorganic nanoparticles with pesticidal capabilities [54]. In a study, utilizing silica-silver nanoparticles to suppress pathogenic fungus (*Rhizoctonia solani, Magnaporthe grisea, Colletotrichum gloeosporioides*), the disease-causing pathogens vanished from diseased leaves after 3 days of spraying the product [55]. Silver nanoparticles were also found to have antifungal action against *Raffaelea sp*., a fungus that causes harm to oak trees [56]. The evaluation of a nanoformulated commercial fungicide (Trifloxystrobin 25% + Tebuconazole 50%) against the soil borne fungal pathogen *Macrophomina phaseolina* at various concentrations (5, 10, 15 and 25 ppm) demonstrated higher efficacy than a commercial product [57].

6.2 Nanofertilizers

A tremendous rise in agricultural yields, particularly grain yields, has played a key role in satisfying the world's nutritional needs during the previous five decades. Increased use of chemical fertilizers is one of the primary contributors to increased crop yield. Fertilizer-responsive crop cultivars have expanded the use of chemical fertilizers. Chemical fertilizers, on the other hand, have a low usage efficiency due to fertilizer loss (through volatilization and leaching), which pollutes the environment and raises production costs [33]. For example, there is a loss of about 50–70% of the nitrogen, when conventional fertilizers are applied. As a result, the scientific community is paying close attention to the development of alternative techniques to assure the long-term usage of nutrients. Nanotechnology is being utilized in this setting to decrease mobile nutrient losses, produce slow-release fertilizers, and increase the accessibility of nutrients that are currently unavailable. Nanofertilizers are nanomaterials that function as carriers/additives for nutrients (e.g., by compositing with minerals) or as nutrients themselves (micro- or macronutrients). Encapsulating nutrients inside a nanofertilizer can also be used to create nanofertilizers. Nanofertilizers boost crop production and quality by supplying more nutrients usage efficiency while lowering manufacturing costs and therefore help in the perspective of agricultural sustainability. It was found that nanofertilizers had a median effectiveness and lead to an increase in the crop yield by 18–29% when compared to traditional fertilizers [58, 59].

Phosphatic nanofertilizers have also been reported to increase the productivity of seeds by 32%. When compared to plants fed with ordinary fertilizer, soybean (*Glycine max* L.) exhibited an increase in yield by 20%. Nanofertilizers are also beneficial to the environment. Plant metabolism and nutrient absorption has been found to improve through nanometric holes molecular transporters or nanostructure cuticle pores. Nanotechnology in plant nutrition enables the creation of slow/controlled release fertilizers, which increase fertilizer efficiency and minimize nutrient losses to the environment, making them more environmentally friendly [60]. Conventional nitrogenous fertilizers have a fertilizer usage efficiency of 30–60%, but chemical bonding in soil causes 80–90% of conventional phosphatic fertilizers to be lost and inaccessible to plants [61]. Clay minerals, hydroxyapatite, chitosan, polyacrylic acid, zeolite, and other nanostructured materials are utilized to produce fertilizers for soil and/or foliar application. Because of hydroxyapatite's large surface area and strong interactions with urea, the release of nitrogen from urea is delayed [62]. Enhanced organic waste decomposition and compost generation might be an important element of nanotechnology in agriculture, although the research is still in its early stages, with no concrete results to yet. Based on the current data, nanofertilizers can minimize the quantity of fertilizer needed owing to their high usage efficiency, therefore reducing the environmental effect of nutrient losses. This discovery comes at an ideal moment to secure global food security.

6.3 Nanobiosensors in agriculture

Biosensors are a type of hybrid receptor-transducer system, a device that detects the physical and chemical characteristics of a medium in the environment to identify the presence of a biological or organic recognition element to detect the presence of a particular biological analyte [63]. Detection of a specific analyte at ultra-low concentrations using a sensitive element by means of a physicochemical transducer Nano-biosensor technology has the potential to revolutionize healthcare, aid in early identification and quick decisions to improve crop production through proper water, land, fertilizer, and pesticide management. A large surface area, fast electron-transfer kinetics, high sensitivity, and a high surface-to-volume ratio. Organophosphates, neonicotinoids, carbamates and atrazines are most common pesticides, and their residues can be found even at low concentrations. Because of the poor homogeneity of the soil, low concentrations last longer. These pesticides are identified using nano-biosensors [64]. Metals (gold, silver, cobalt, etc.) NPs, carbon nanotubes (CNTs), magnetic NPs, and quantum dots (QDs) have all been studied for their uses in biosensors, which have become a new multidisciplinary frontier between biological sensing and material research. As a result, a biosensor is a device that incorporates a biological recognition element as well as physical or chemical principles. It combines a biological and an electronic component to produce a quantifiable signal component, with biological recognition accomplished via the transducer process and signal processing accomplished by electronic accomplishment. The existence of a bioreceptor (biological element) paired with an appropriate transducer that creates a signal after contact with the target molecule of interest gives biosensor systems a greater specificity and sensitivity than conventional techniques. Enzymes, dendrimers, thin films, and other natural and artificial bioreceptors have recently been created and utilized. As a result, a biological reaction is converted into an electrical signal by a biosensor, an analytical instrument. It's about the components of biological elements including antibodies, enzymes, proteins, and nucleic acids. The transducer, as well as any accompanying electronics or signal processors, are in charge of detecting the functions. The AuNP-based micro cantilever-based DNA biosensor has been created and is commonly used to detect low levels of DNA during a hybridization procedure [65]. Although, usage of nanotechnology has created new revolution in smart farming and lowered related concerns, broad usage of nanomaterials -based agriculture and food items and less-likely immobilized nano-sensors have risen impacts on human and environmental health. Complexity of nanobio-eco-interactions restricts tracking their activity in soils. Therefore, a comprehensive approach is required to comprehend these connections in soil-plant-air and eventually in food chain.

6.4 Soil remediation using Nanomaterials

Soil is an important element of the ecosystem that has been under threat for decades owing to numerous forms of pollution. Soil recovery and regeneration has become a global issue. Nanotechnology has recently emerged as an effective, cost-effective, environmentally friendly, and promising soil remediation technique. This technique offers a lot of promise for removing pollutants from the environment through adsorption, redox reactions, conversion, stabilization, and other methods. To remove pollutants from soil, a variety of nanomaterials and devices are employed. As a result, soil might be efficiently remediated using nanotechnology-based concepts, techniques, and products, which are not possible to do using traditional approaches. Heavy metal is one of the most dangerous soil pollutants. Heavy metals, like other pollutants, might be removed from soil utilizing nanotechnology-based methods.

Bioremediation is an in situ, natural, environmentally friendly, cost-effective, and flexible approach to detoxify hazardous contaminants (organic and inorganic). However, due to extended treatment times, low pollutant availability, low remediation efficiency in highly polluted soils caused by pollutant toxicity to biological agents (bacteria, fungus, plants, and so on), and the generation of hazardous byproducts, its efficacy may be restricted [66]. The use of nanomaterials in conjunction with bioremediation provides a method for overcoming the constraints of this green technology. Although nanomaterials have been utilized for chemical decontamination of sites for the past two decades, their application in bioremediation is a relatively new area that is still in its early stages.

7. Future of nanopesticides and pest control

Excessive use of pesticides and fertilizers in agriculture to boost yields has shown to be ineffective since a substantial portion of them is wasted, causing harm to the environment and human health. As a result, farmers have a significant difficulty in replacing pesticides and fertilizers with nanopesticides [67]. Over the last few decades, considerable research into the application of nanotechnology to increase agricultural production has been undertaken. The use nanoparticles as nanopesticides have been proven to be successful in the agri-food production. Herbicides, fungicides, pesticides and fertilizers are encapsulated with different types of nanoparticles that aid in the delayed release of fertilizers and pesticides, which results in precise dose availability to crops. [68]. The chemically designed fertilizers are inorganic compounds or materials with specified chemical composition and mostly synthetic in origin. They are primarily involved in agriculture sector to provide nutrients like potassium, nitrogen and phosphorous that is not present in soil. However, to the loss of these fertilizers from the soil due to leaching, volatilization and water runoff is a major problem associated with their use.

The release of these fertilizers causes environmental degradation and a significant quantity of nutrients is lost and therefore inaccessible to the plants [69]. In agriculture pesticides are used to control pests, rats, mice, ticks, mosquitoes and other disease carrier. In addition to those pesticides are being used to control disease, insect infection and weeds. Currently using of pesticides is the fastest way to control effects of various pests and diseases. The usage of pesticides in agriculture is associated with number of risks which includes harmful effects on pollinating and domestic animals, effects on human health, penetrate into the water and cause toxic effects on aquatic animals and finally effects on our ecosystem. The programmed and regulated usage of chemicals on a nanoscale basis is an acceptable and suitable solution of the difficulties described above. In a controlled manner way, these ingredients are injected directly into the plant portion that has been attacked by the disease or insect [70].

Nanofertilizers are the modified forms of traditional chemical fertilizers designed through nanotechnological interventions and a variety of biological and physiochemical techniques. Nanofertilizers have unique properties which differs it from bulk materials [71]. Nanofertilizers have various advantages over the traditional fertilizers such as higher solubility and bioavailability, release of nutrients in controlled and slow manner and less loss rate [72]. In present condition, meeting the dietary needs of the world's fastest growing population is pressing necessity. It has been estimated nearly one third of crops get damaged due to pest infestation by applying conventional methods. There is an immediate requirement of innovative methods to overcome these issues. In this aspect nanotechnology is playing a leading role to the agro technological revolution [73]. With the help of these cutting–edge materials, modern agriculture is evolving into smart farming allowing farmers to get the most out of their resources. Nanotechnology is not limited to the plant against pest control in addition to that it monitors plant growth, enhanced crop yield and minimizing waste. Nanomaterials in the form of nano insecticides, nano fungicides, nano herbicides and nanonematocides are the most often tested nano pesticides. The nanomaterials utilized as nanopesticides can be metal nanoparticles like silver nanoparticles, gold nanoparticles and copper nanoparticles or metal oxide nanoparticles such as zinc oxide nanoparticles, copper oxide nanoparticles, silicon dioxide, magnese dioxide or titanium dioxide etc. Studies conducted on silver nanoparticles at 30–150 mg/dl against *Meloidogyne spp*. have showed the 99% reduction of nematodes [74]. In another study silver

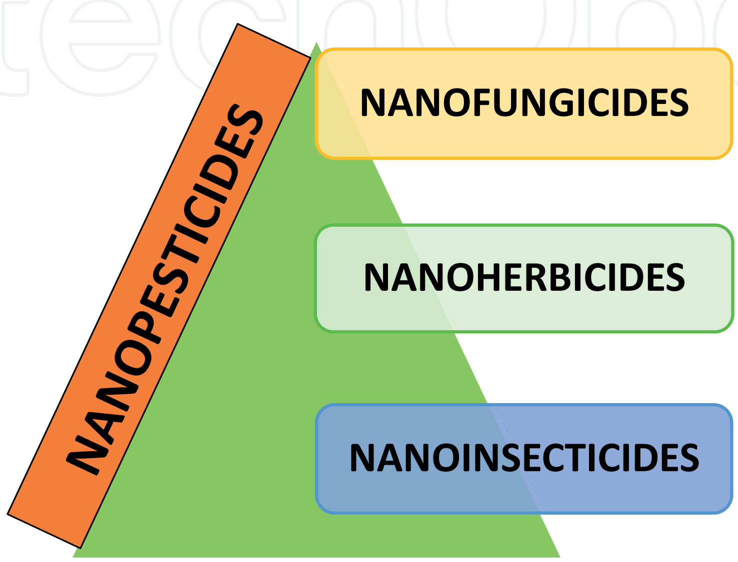

Figure 2.
Different types of nanomaterials used against plant protection.

nanoparticles used as nanopesticides against *Xanthomonas campestris pv. campestris* have shown the significant reduction of bacteria causing bacterial blight disease [75]. Copper nanoparticles when used against *Fusarium spp*. has shown excellent antifungal activity as nanopesticide. In another study conducted on copper oxide when used at a concentration of 10 mg/L against *S. littoralis* showed good insecticide on Bt-transgenic cotton [76, 77]. Iron oxide nanoparticles when used against fungal pathogen like *Rhophitulus solani, B. cinerea* and *F. oxyporium* have showed the reduction of fungal infection about 60–80% [78]. Magnesium oxide nanoparticles when applied against fungal pathogen *F. oxyporium* reduces the disease in tomato plants [79]. Gold nanoparticles-ferbam with a size of about 30 nm when applied in tea leaves promoted surface adhesion in tea plant [80]. In **Figure 2**, we show the different types of nanoparticles that are used as nanopesticides for crop protection.

8. Conclusion

Global food security is one of the major concerns that both developed and developing nations are undertaking from the time of global human population upsurge. Global crops lands are limited and global population is rising at an alarming rate. Since, the extension of agricultural activities has brought the increase in the production of synthetic agricultural pesticides and fertilizers that have been used by the farmers for decades all over the world. The large-scale utilization of these synthetic agrochemicals from the time of their evolution to the present era has cost the humans; their health, air pollution, water pollution, soil pollution, decline of the beneficial entomofauna, environmental contamination and so on. Implementation of alternative measures to overcome the use of synthetic pesticides and fertilizers is need of the hour. With the advancement of the technology, the novel approach of the nanotechnology can bring agriculture towards the sustainability. The novel nanopesticides and nanofertilizers are the best alternatives to save the crops, human health and the environment. The regulations must be employed and quality control ought to be instigated for the utilization of nanomaterials in the agriculture.

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