# 6 Current Scenario of Nanomaterials in the Environmental, Agricultural, and Biomedical Fields

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## 6.1 INTRODUCTION

The application of nanotechnology in biomedical sciences and other fields has increased drastically due to elevated research output. Many fields have now positively adopted the utilization of nanotechnologies for alternative energy and environmental sources, physics, biomedicine, electronics, agriculture, and engineering. Moreover, the application of nanotechnology in biomedicine is unprecedented as cellular uptake, and encapsulation of hydrophobic photosensitizers in fluid nanocarriers may increase treatment options. Through nanotechnology, the intracellular milieu environment can be changed, and enzymatic degradation prevention and reduction in cytotoxicity of many toxicants can also be achieved [1].

It has been revealed that nanoparticles possess a unique physicochemical property that enables them to be very useful for many biomedical applications such as attachment to other biomolecules to form nanoparticle–biomolecule conjugates with tremendous capacities in drug delivery, clearance, absorption, and metabolic processes. The adoption of nanotechnology in biomedical sciences has increased therapeutic efficacy, eliminates many adverse effects, lowered wastage plus increasing bioavailability of drugs at various sites over the traditional therapeutics. Again, in biomedical imaging, nanoparticles or nanobased products are utilized for the diagnosis of a disease condition, cancer treatment, chronic diabetic wounds, intracellular mRNA delivery, drug delivery, polymicrobial infection treatment, genetic disorders plus gene therapy in clinical treatment particularly for protein replacement therapies, vaccination, plus genetic disease management [2,3]. Also, numerous studies have been performed by numerous scientists to establish the usefulness of nanomaterials in agriculture most especially as eco-friendly biopesticides, insecticides, and weedicide that could affect an increase in agricultural products [4–7].

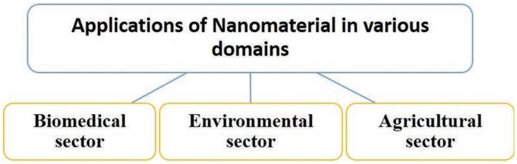


**FIGURE 6.1** The various applications of nanomaterial are shown in numerous fields.

Hence, this chapter will provide detailed information on the numerous types and roles of nanomaterials in resolving several challenges encountered in the environmental, agricultural, and biomedical fields. The various applications of nanomaterial are shown in numerous fields as illustrated in Figure 6.1.

## 6.2 APPLICATION OF NANOMATERIAL IN BIOMEDICAL FIELDS

The nanomaterials have a vast range of applications in the field of biomedical, which is demonstrated in Figure 6.2 and is further explained in the subsections below.

### 6.2.1 Antibacterial, Antifungal, and Antiviral Activities

Lesley et al. [8] revealed that nanotechnology has brought about many innovative approaches to the food and agricultural sector particularly in the aspect of antimicrobial nanoparticles against pathogens in the poultry industry. The authors investigated the use of nanoparticles against *Salmonella spp.* and *Campylobacter spp.* to evaluate the in vitro activity of these nanoparticles in the poultry industry. The results revealed that the nanoparticles are very effective in a concentration-dependent manner against the pathogens. Azam et al. [9] described that nanomaterials as antibacterial agents have been utilized in the food industry against many foodborne bacterial

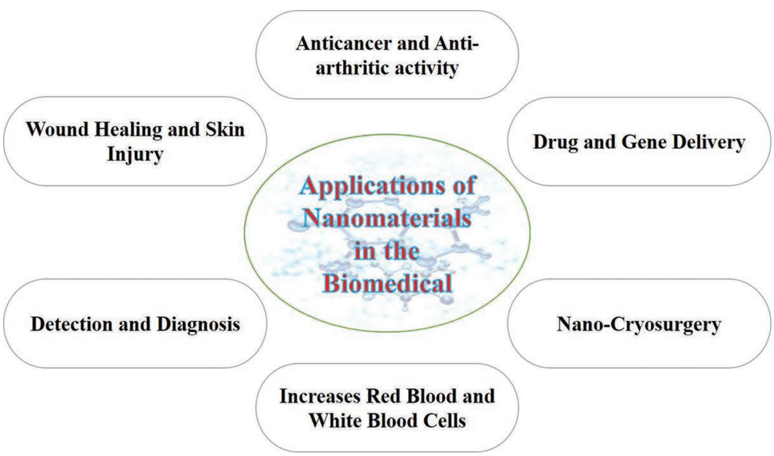


**FIGURE 6.2** Schematic illustration of the nanomaterials in the biomedical domain.

such as Campylobacter strains, Salmonella strains, and gastroenteritis. The authors further suggested that these nanomaterials should be incorporated in packaging and crate design in poultry through nanoscience.

Zhen-Xing and Bin-Feng [10] demonstrated that pollution has resulted in serious environmental and human health concerns. The most troublesome of these are bacterial pollution and contamination; thus, suggestions have been given to utilize nanoinorganic metal oxide to help reduce the detrimental effects of bacterial pollutions. The authors revealed that MgO nanoparticles offer promising antibacterial mechanisms in a concentration-dependent manner that could be linked to their great resistance to harsh conditions during processing. They revealed that the proposed mechanisms by which MgO nanoparticles perform their antibacterial effects are through direct damage to the bacterial cell, development of reactive oxygen species, and interface of nanoparticles with bacteria in alkaline effect.

Tsuneo et al. [11] performed an investigation on the potential application of silver nanoparticles on virus surface receptor proteins. It is generally regarded as silver nanoparticles causing anti-inflammatory properties or as antiviral agents in allergic reactions, through blockade of viral attachment, disulfide bonds with a thiol group, binding to gp1 20, viral neuraminidase activations, degradation, and apoptosis. The silver complex formation also occurs in cancer cells destroying DNA base pairs. Benton et al. [12] reported that the fabrication of silver nanoparticles as antibacterial agents has been discovered for ages with potent efficacy against bacteria pathogen involving damage plus inhibition to the elongated peptidoglycan bacteria cell wall or damage of lipoprotein at C-, N-terminals by Ag+ ions through autolysins. Orlowski et al. [13] suggested that silver nanoparticles have been utilized as antimicrobial agents with efficient inhibitory properties against several viruses.

Lei et al. [14] showed that silver nanoparticles have many industrial applications including antiviral properties through direct interaction between extracellular virions and viral RNA with nanoparticles causing inhibitory effects. Hu et al. [15] revealed that viral amino acid enzymes like hydrolase, neuraminidase, hemagglutinin, aspartate, and glutamate are largely responsible for the catalytic action and initiation of virus degradation when activated by nanoparticles. The authors suggested that the proteasome pathway may be involved in the degradation process of the virus by nanoparticles in the host cell. Gaikwad et al. [16] demonstrated that endolysins are enzymes utilized by bacteria after replication to damage the cell membrane peptidoglycan causing the release of progeny virion. This may be a target for nanoparticle mechanisms in their antiviral activity. Mori et al. [17] revealed that silver nanoparticle interaction with the virus causes DNA damage by the induction of reactive oxygen species and silver complex formation resulting in antiviral activities. Liangpeng et al. [18] showed that silver nanoparticles have antibacterial capacity against a broad spectrum of bacterial pathogens, which is size-, shape-, and dose-dependent. The authors also suggested that nanoparticles can be combined with antibiotics to increase their antimicrobial effects by interaction with phosphorus-containing bases or regulate signal transduction mechanism of phosphotyrosine bacterial peptides causing inhibition of cell division.

Liangpeng et al. [18] revealed that the antifungal activity of nanosilver is second to none with a potent effect against *Candida* spp. The proposed mechanism involves the destruction of the cellular membrane, with the inhibition of budding activity. In another experiment done by Azam et al. [9], it was revealed that metallic nanoparticles have received massive attention from different fields due to their broad spectrum of actions and physiochemical properties. They also noted that the antibacterial and antifungal effects have been reported by different authors. Sumon and Tamalika [19] revealed that metallic nanoparticles can be produced through green technology with antibacterial properties generating reactive oxygen species and destruction of genetic materials. Wu et al. [20] demonstrated that the global threat faced with antibiotic-resistant microorganisms is becoming enormous; thus, metallic nanoparticles may be an alternative way to prevent completely the progression and development of multidrug-resistant microorganisms. Ahmed et al. [21] suggested that silver nanoparticles in combination with microbes will lead to binding of the nanoparticles with the cell membrane, membrane sulfur interaction, morphological changes, separation, damage to intracellular structures, and swelling. Humberto et al. [22] revealed that advances in bionanotechnology have brought change to the therapeutic horizons due to their nontoxic effects.

Yasutaka et al. [23] reported that silver nanoparticle composites with chitosan have potent antiviral properties against influenza A virus in a size-dependent manner as compared with the individual molecule. Verónica et al. [24] determined an in vitro antibacterial property of dental interim improved with terpenes cement combined with nanoparticles. From their analysis and results, they discovered that supplementation of the nanoparticles with terpenes increased the antibacterial activity against *S. mutans* ATCC 25175 and elevated the diametral tensile strength. Guilherme et al. [25] discovered that spread of pathogenic microbes over the years has significantly increased across the globe; thus, urgent attention is needed to develop various technological approaches as means of reducing or eliminating the cause. The authors proposed that the application of nanoparticles in the inhibition of the SARS-CoV-2 virus and other bacteria could offer a great deal of opportunity. Naeima and Hanan [26] revealed that silver nanoparticles have received great attention for their antibacterial activity. The authors produced silver nanoparticles from *Datura stramonium* plant to analyze its antibacterial characteristics against different bacterial pathogens and later confirmed its huge beneficial effects as an antibacterial agent.

Muhamed et al. [27] revealed that metal oxide nanoparticles in combination with specific bioactive molecules have been utilized in different fields with beneficial properties, particularly in biomedical sciences. Various combinations have been discovered in the past, but the authors investigated the role of functionalized curcumin aniline generated from turmeric plants combined with manganese nanoparticles produced from green synthesis against bacterial and fungal strains. From the results obtained, it was discovered that the combination displayed a significant increase in antimicrobial activity, thereby suggesting a new intervention approach to treat patients. Nurit et al. [28] briefly reported that serious attention to develop new material as an antibiotic agent has been witnessed over the past few decades due to increased resistance to many synthetic antibiotics; thus, the advancement of nanotechnology has brought significant progress to develop antimicrobial biological agents as bactericidal plus fungicidal to prevent biofilm-linked infections or drug-resistant microbes.

Mogomotsi et al. [29] briefly reported that phytomedicine and nanobiotechnology can be combined for biological purposes in a cost-effective and eco-friendly manner for pharmacological applications. Thus, the authors synthesized biogenic silver nanoparticles and investigated the antimicrobial action against different bacteria species and discovered that the silver nanoparticles displayed a higher level of antimicrobial activity. Clarence and Geoffrey [30] demonstrated that the conventional antimicrobial agents have displayed weak response to many antimicrobial-resistant strains of bacteria resulting in global concern and hence the search for alternatives such as nanoparticles with vast spectrum antimicrobial effects with tremendous physiochemical plus functionalization characteristics. Lavanya et al. [31] reported that there is a serious need to develop a potent treatment for infectious diseases due to the adverse side effects caused by prolonged use of some antibiotics and fast drug resistance development. They revealed that the relationship between microorganisms and nanoparticles has reshaped the field of biomedical sciences for therapeutic and diagnostic purposes.

Farouk et al. [32] showed that nanotechnology has created an alternative for the treatment of pathogenic fungal, viral, and bacterial as they offer prolonged treatment with minimal side effects. Zarrindokht and Pegah [33] demonstrated that ZnO nanoparticles possess antibacterial properties against many pathogenic organisms. Thus, they evaluated the bacteriological effects on *S. aureus* and *E. coli*. They discovered that the antibacterial activity of ZnO nanoparticles improved with a reduction in the size of the particles. Azam et al. [9] showed that metallic nanoparticles have wide applications in chemistry, medicine, biotechnology plus agriculture. Hence, the authors synthesized silver and copper nanoparticles with environmentally friendly materials of different plant species and evaluated the antibacterial and antifungal effects. From the results they obtained, it was observed that silver nanoparticles yielded notable positive effects. Chiriac et al. [34] demonstrated that infectious diseases caused by pathogenic organisms have resulted in a serious global burden due to the development of resistance to many synthetic drugs currently used in their management. The authors then carried out the test on different nanoparticles to establish a potent antibacterial-based nanoparticle and thus discovered that zinc-based nanoparticles have the strongest antibiotic effects and ability to cause membrane and protein damage with oxidative stress.

Carin et al. [35] reported that the antimicrobial properties of silver nanomaterials combined with other materials. The authors suggested that excellent ionic movement characteristics of the materials permit the faster release of ion plus cell damage. Bankier et al. [36] demonstrated that metallic nanoparticles have potent antimicrobial characteristics making them suitable for pharmaceutical uses. Thus, the authors evaluated the combined effects compared with single use and discovered that the combination resulted in more significant antimicrobial effects. Patcharaporn et al. [37] showed that nanotechnology possesses good antibacterial activity in vertebrates; hence, they synthesized a nanoparticle from eco-friendly *Aloe vera* leaf extract with antibacterial effect. Jo et al. [38] showed that very few studies have applied nanotechnology in controlling plant diseases; hence, the authors tested the role of silver ion nanoparticles as an antifungal against *Magnaporthe grisea* and *Bipolaris sorokiniana*. Their findings indicated that the silver nanoparticles displayed a strong antifungal effect against the two plant-pathogenic fungi by promoting the direct effect of silver with germ tubes and spores, plus inhibiting their viability.

Jana and Seth [39] revealed the application of nanoparticles in modern-day lives and thus reviewed organic- and inorganic-based nanomaterials as antimicrobial agents. They went further to and elaborated on the roles of nanomaterials-based superhydrophobic coatings in biomedical sciences particularly helping to tackle the present COVID-19 disease. Hassan [40] described how devastating the nosocomial pathogenic infection can be particularly for immunocompromised patients and the development of multidrug-resistant bacteria plus the growing concern of biofilm-linked infections has led to the search for novel treatment. Recently, the utilization of nanotechnology in clinical practice has led to significant improvement particularly in the management of infectious microbial diseases; thus, the authors reviewed the extent of multidrug resistance in nosocomial infections, mechanisms of invasion, drug resistance, and the effects of nanomaterials as antimicrobial agents. Atiqah et al. [41] described how the development of nanomaterials has been on the increase due to their wide industrial applications. The authors evaluated the antiviral and antibacterial mechanisms of silver nanoparticles and added a note on the possible toxicity of their biological applications. Tiwari et al. [42] reported that multidrug-resistant *Acinetobacter baumannii* against Carbapenems has become a significant issue that might be linked to the increased number of mortalities recorded with its application. Thus, the authors search for alternative ways to develop nanoparticles as antibacterial agents against carbapenem-resistant *A. baumannii* and the possible mechanisms of action. They proposed that the mechanisms of action could be increased membrane lipid peroxidation, elevated reactive oxygen species, DNA, and protein damage plus reduction in cell viability as zinc oxide nanoparticles showed a strong antibacterial effect against carbapenem-resistant *A. baumannii*.

Ayeshamariam et al. [43] revealed the antifungal and antibacterial of tin oxide nanoparticles with Aloe vera extract against several pathogenic bacterial and discovered that tin oxide nanoparticles with Aloe vera extract displayed a strong effect on the tested microorganisms. Hamsa et al. [44] demonstrated that silver nanoparticles utilizing *Cinnamomum zylinicum* bark extracts are a great antimicrobial agent against different pathogenic bacteria and hence recommended that they could be utilized as antibiotics against multidrug-resistant bacteria.

### 6.2.2 Anti-ulcer Activity

Sreelakshmy et al. [45] briefly described that silver nanoparticles utilizing *Glycyrrhiza glabra* could be of great benefit for treating gastric ulcer disease. The authors revealed that the plant has not been documented for any in vitro anti-ulcer properties particularly for *H. pylori*; thus, they investigated silver nanoparticles obtained from *Glycyrrhiza glabra* root extract for in vitro anti-ulcer activity**.** They discovered that the nanoparticles showed potent cytoprotective anti-ulcer effects against *H. pylori*. Rangabhatla et al. [46] revealed the ulcer protective activity of cerium oxide nanoparticles in an animal model during their experiment on ethanol-induced gastric ulcers. They discovered that these nanoparticles were able to display strong ulcer inhibition as compared with ranitidine. The observed mechanisms were mopping of reactive oxygen species, increasing antioxidant defense system.

Fatma et al. [47] revealed that amoxicillin and doxycycline broadband antibiotics were utilized as nanocomposite in treating animal and human model experiment disease. Ethanol was utilized for ulcer induction and evaluation of wound closure rate, acute toxicity, healing percentages, protective rate, histopathological plus ulcer index were done. The findings revealed that the nanocomposites showed significant ulcer prevention and were approved for biomedical and pharmaceutical applications. Paul et al. [48] briefly reported that Uapaca staudtii Pax has strong anti-ulcer and antioxidant activities in reserpine- and indomethacin-induced ulcer models. The findings revealed that the extracts possess highly significant antioxidant and anti-ulcer properties as compared to the standard drugs and could be utilized in nanoparticle development in managing ulcer disease. Prakash et al. [49] showed that eroding the epithelial lining of the stomach, small intestine, and duodenum may lead to ulcer formation. In their study, it was revealed that many pathogenic bacteria may induce ulcer due to the release of toxins, while several drugs have been utilized in the past with little disadvantage like side effects, drug interactions, and relapses; thus, novel nanoparticles based-anti-ulcer drugs are now being suggested.

Anil et al. [50] revealed the potent advantage of cerium oxide nanoparticles as anti-ulcer, antisecretory plus antioxidant agent. In an experiment conducted by the authors, it was revealed that pyloric ligation with aspirin-induced gastric ulcer was treated with nanoceria and cerium oxide nanoparticles. It was observed that significant effects were displayed by cerium oxide nanoparticles by lowering the gastric volume, acidity, pH, plus ulcer index due to their vast surface-to-volume ratio plus physicochemical characteristics.

### 6.2.3 Antiallergic Activity

Sozer and Kokini [51] revealed that silver nanoparticles have attracted wide acceptance in biomedical applications particularly in treatment, diagnosis, drug delivery, and medical devices. The authors showed the physiological and physicochemical properties of silver nanoparticles in antifungal, antibacterial, antiviral, anti-inflammatory, and antiallergic reactions. The authors showed that silver nanoparticles significantly reduced pro-inflammatory cytokines, goblet cell hyperplasia, tumor necrosis factor-alpha, immunoglobulin E, IL-4, interleukin-10 plus transforming growth factor-beta expressions in dermatitis allergic reaction plus allergic rhinitis.

Saadatzadeh et al. [52] revealed that food allergenicity can be an adverse immune response to certain proteins or epitopes with severe response or effects on different organs. Many approaches have been applied to mitigate against food allergies, and the authors evaluated the adoption of novel technology such as nanotechnology as an alternative measure. Zimet et al. [53] demonstrated that soy allergens have increased drastically in Western countries as a result of increased consumption of soy proteins; hence, many strategies are put in place to reduce the allergies or immunoreactivity produced by the consumption of soy products. Nanotechnology has been identified as one of the best options for reducing the effects of food allergies. Patrignani et al. [54] revealed that higher allergenicity is produced from the milk of ruminants; hence, efforts have been put in place to reduce the allergenicity with the adoption of nanotechnology. Lanciotti et al. [55] demonstrated that allergies from fruits and vegetables have been on the increase; thus, many approaches to reduce food allergy have been adopted in many Western countries. One of the fast-growing fields of science with the capacities to reduce the allergenicity of food, fruit, and vegetables is the utilization of nanotechnology such as the combination of pectinase with metallic ion nanoparticles to reduce allergenicity.

### 6.2.4 Effects on Central and Peripheral Nervous Systems

Cristina et al. [56] reported that the nervous system is a neural network connecting the spinal cord, brain, and other systems; thus, nanoparticles can be taken or absorbed from the diverse route in the body such as dermal, olfactory mucosa, neuronal, or nerve pathways. These nanoparticles may find their way into the blood–brain barrier where they may interact with many sensory nerve endings and mitochondria and then into other deeper brain structures through the blood–brain barrier. The authors have revealed that the blood–brain barrier may preferentially select the entry of cationic molecules due to its anionic nature. This route may be utilized for drug delivery into the brain and other nervous tissues; hence, the passage of nanoparticles may be influenced by the specific charge on it.

Studies have revealed that many neurodegenerative diseases are a result of the accumulation of metallic compounds and neuronal uptake of nanoparticles causing functional damage, myelin sheath breakdown due to oxidative stress, and toxicity. In the treatment protocol for managing these conditions, metal chelators and antioxidants may be beneficial as they can permeate through the blood–brain barrier system and initiate the therapeutic process.

## 6.3 APPLICATIONS OF NANOMATERIALS FOR THE TREATMENT OF THE HEAVILY POLLUTED ENVIRONMENT

The nanomaterials have a variety of applications in the environmental domain, which is highlighted in Figure 6.3, and the role of nanomaterials for the treatment of pollutants found in the environment such as pesticides and polyaromatic hydrocarbon is demonstrated in the below subsections.

### 6.3.1 Pesticides

In the past 50 decades, there have been indications of persistent demand for food, which has led to the sharp rise in the pressure on agricultural resources globally, as a consequence of increased human population growth. In an attempt to manage this growth and sustain the pressures placed on agricultural resources, many producers have engaged in the use of pesticides to control the invasion of pests and pathogenic agents into agricultural produce. Also, postharvest storage of crops and other agricultural products has utilized the adoption of pesticides and synthetic chemicals to prolong the storage rate and to prevent the invasion of pest and pathogenic organisms. Many studies have revealed that the adoption and utilization of these chemicals

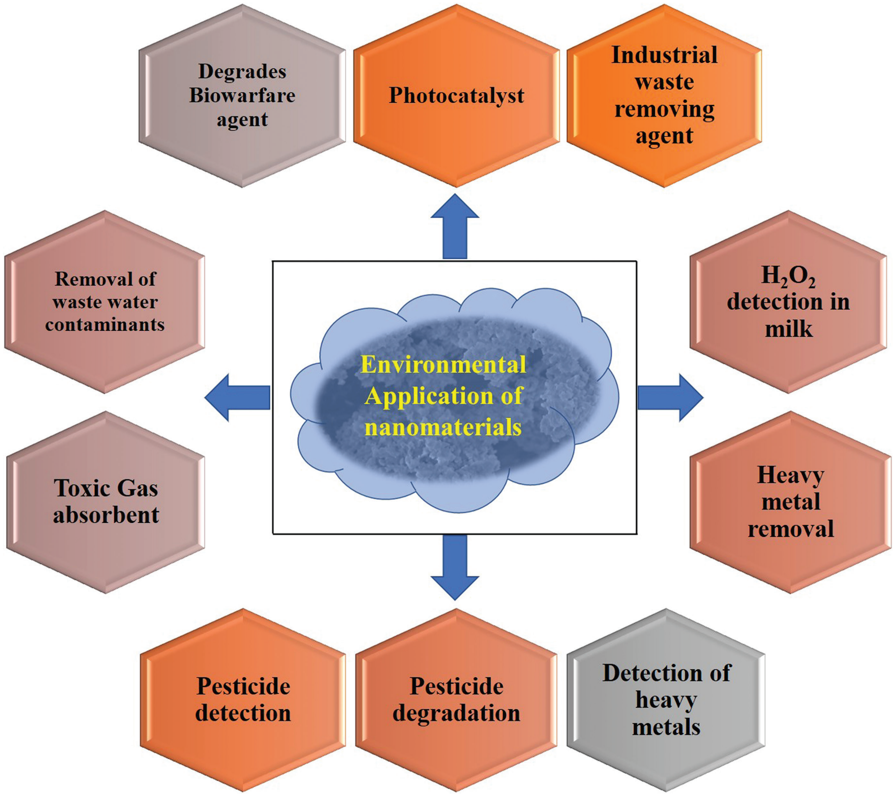


**FIGURE 6.3** Applications of nanomaterials in the environmental field.

and pesticides have led to increased environmental pollution and resulted in adverse effects on human health. Thus, in an attempt to reduce the utilization of synthetic chemicals like pesticides, many novel technologies are attracting serious attention among scientists across the globe. One of these technologies suggested involves the development and adoption of nanopesticides and nanofertilizer as alternatives to synthetic chemicals with toxic chemicals, which have adversely caused serious environmental concern. Khan and Rizvi [57], in a review, looked at the utilization of nanopesticides and nanofertilizer in the improvements of crop protection, production plus ensuring environmental protection. The authors recounted that many nations have employed several measures like the green revolution in the provision of food security to meet the growing population and reduce environmental pollution. The utilization of novel technologies such as nanotechnology in the improvement and conservation of farm resources is needed at this present time to supplement the already existing technology. This technology has such great potential that can change the narrative of agriculture and associated fields in the aspect of environmental health, pest protection, and crop productivity. The authors concluded by stating that the use of nanotechnology in modern agriculture will boost food security in an emerging, challenging, and uncontrolled population setting. They also noted that nanotechnology would improve agricultural sustainability, productivity, pest protection, and delivery devices for effective improvement in crop production and the suppression of disease or pest invasions. The authors also reported that the issues of indiscriminate use and misuse of nanomaterials or utilization of pesticides and fertilizers can result to rebound toxicity in the agricultural and environmental systems. To curtail this, they recommended more research in the area of biosafety of nanoproducts for agriculture use and environmental sustainability.

Iavicolia et al. [58] did a review of occupational and toxicological risks in the utilization of pesticides in farming activities. They stated that this approach has the latency to make a sustainable influence on several ecological problems in forestry and agriculture like justifiable management of the agricultural resource, energy restraints, and urbanization. Nonetheless, they reported that human and environmental hazards may sprout up from the utilization of synthetic pesticides in an attempt to preserve and enhance agricultural productivity and thus suggested the utilization and adoption of nanopesticides and nanofertilizers as alternatives. The authors later proposed risk management and ecological assessment as well as biosafety and life cycle analysis to understudy the possible toxicity fate in the application of nanochemicals (nanopesticides and nanofertilizers) for agricultural purposes. Besides, the interaction of ecological stressors and coformulants should also be put into considerations when assessing the fate of the nanochemicals.

For the past several decades, residues from pesticides and pollutants in the environment have contributed immensely to serious health and environmental risks witnessed today. Several attempts had been made to mitigate this negative impact of pesticides on food, the environment, and human health; however, little progress has been seen particularly in developing countries. Firozjaee et al. [59] did a review on the decontamination of pesticides from the aqueous mixture using effective nanotechnology. This technology aids in the final mineralization of residues in pesticides to a less or non-noxious form. This technology offers countless hidden benefits such as uplifting or enhancing the already existing technologies (degradation, filtration, and adsorption) by employing novel nanomaterials for efficient consumption of materials plus energy. They proposed the application of nanotechnology in the decontamination of pesticides on farmland. The multitude-of-parameters method was also suggested for the enhancement of nanomaterials in aqueous solution for the deletion of residues of pesticides. This method would aid the process involved in the intensification of the surface area of nanomaterials in the solution and thus incorporates its reactivity. The authors suggested the application of nanotechnology in the elimination of pesticides in related media like wastewater and water purification to reduce the health and environmental risks linked to the media.

Urkude [60] did a review on the management of pests by the application of nanomaterials in pesticides. The author reported that the indiscriminate use of pesticides in the control of pests in agriculture has resulted in severe health and ecological problems, even though its application is beneficial in securing farm products. They stressed that nanotechnology is one of the efficient tools in resolving issues related to the pollution of soil in agriculture. The use of nanopesticides for the management and control of farm pests has yielded proper efficiency, decreased pollution, and spurred the farmers to meet up with some uncertain tasks that could not be achieved before like enhanced farmer's efficiencies. It has also improved the delivery system of farm pesticides to solve this problem of bioefficiency. They also reported that some nanopesticides formulation has shown great potential in eliminating and controlling pest rebounds as well as detectable pesticide residues in the soil. They suggested nanopesticides as an ecological footprint in the management of pests' rebound and heavily polluted environment.

Elizabeth et al. [61] in a review examined the management of flora pests using nanotechnology. The authors reported that about 20%–40% of agricultural products are destroyed by plant pathogens and pests yearly. The containment of these pests depends on existing technology like chemical usage such as synthetic pesticides, which are toxic to the plants, crops, animals, humans, and the environment. Thus, nanotechnology is believed to offer a better alternative and sustainable means of decreasing the toxicity level of these chemicals, enhance the shelf-life as well as the solubility potentials of the pesticides in the medium used, thus influencing the environment positively. The authors reported that nanoparticles can act in two ways, as a protectant and a delivery system for RNA molecules, herbicides, fungicides, and insecticides. However, there lie the benefits linked with the utilization of nanomaterials for the application and commercialization of agriculture in both field trials and farm settings in the management of pests and improvement in crop production. The authors concluded by recommending that biologists, agriculturists, environmentalists, physiologists, and other relevant stakeholders should synergize to bring expertise in resolving the inefficiency pervading the incidences of pest rebound and crop nonproductivity.

Sahithya and Nilanjana [62], in a review, examined the application of nanomaterials in the redress of pesticides in wastewater. They stressed that the rigorous application of pesticides for agricultural purposes has elicited severe ecological and health issues. Different artificial chemicals have been utilized for decades in the cleanup of pesticides from the water environment. However, it has been recognized that bionanoparticles have proven to be effective in the cleanup of pesticides, through the use of photocatalysts or adsorbent techniques. They stated that this method is cheap, less toxic, eco-friendly, and sustainable. They suggested a similar method in cleaning up polymer materials by employing biopolymers with nanomaterials on a large scale.

### 6.3.2 Polyaromatic Hydrocarbon

Hassan et al. [63] tested the use of iron oxide nanoparticles (IONPs) in the elimination of micropollutants (benzo(a)pyrene and pyrene) from wastewater through the process of adsorption. The authors stated that benzo(a)pyrene and pyrene congeners of polycyclic aromatic hydrocarbons (PAHs) even at reduced concentrations are highly carcinogenic. Several environmental factors like PAHs concentration, temperature, pH as IONPs concentration, affecting the potential remediation via adsorption of PAHs, were examined and evaluated. The outcome of the study showed that the highest capacity of IONPs against benzo(a)pyrene and pyrene was 0.029 and 2.8 mg/g, respectively. The outcome of the thermodynamic reaction revealed an adsorption exothermic process of benzo(a)pyrene and pyrene. The isotherms and kinetic investigations showed that the process of adsorption followed pseudo-2° actions and followed the Langmuir isotherm model. More so, the IONPs demonstrated to be an effective contender for the adsorption of benzo(a)pyrene and pyrene after five generation cycles at the degree of 99% and 98.5%, respectively.

Yang et al. [64] evaluated the adsorption of PAHs like pyrene, phenanthrene, and naphthalene and six chains (fullerenes) using carbon-based nanoparticles (CNs). The authors stated that CNs are newly produced particles that have great potential in the control of hydrophobic organic compounds (HOCs) through adsorption and also regulate their transformation as well as their fate in the ecosystem. It was observed that the sorption process was isothermal and not linear. It was well fitted with the Polanyi–Manes model (PMM), producing a characteristic curve that depends on the nature and properties of the CNs. It was observed that the sorption process correlated with the volume and surface area ratios of the micropore to the mesopore. However, the increased sorption capacity of the polyaromatic hydrocarbons by the CNs might lead to possible environmental hazards when released. This action can also result in a sudden change in the bioavailability and the fate of the PAHs in the ecosystem.

PAHs are environmental contaminants that have high bioaccumulation potentials, nonbiodegradable, highly noxious, and ubiquitous. For the past 50 decades, there have been several techniques used in the control of PAHs in the environment. However, a more reliable and environmentally friendly technique has been proposed by many scientists. In line with this trend, Rani and Shanker [65], in a review, evaluated the remediation potentials of nanomaterials on PAHs. The authors hinged on rapid industrialization and population burst as the chief precursors of the release of PAHs into the environment. The use of nanoparticles to control PAH's influence on the environment is one of the novel technologies invoked. The application of nanotechnology uses the principles of redox breakdown, photocatalytic, and adsorption in the removal of PAHs in the environment. Among all these techniques, the adsorption method was singled out as one of the best because it is efficient and equally cheap to use. The authors also suggested the utilization of native methods like photolysis and microbial degradation as well as some conventional technique like activated carbon and biological wastes from agriculture. They stated some of the benefits of using nanomaterials as an indelible tool for PAHs removals like their low cost, green technology, high adsorbent quality under sunlight and UV irradiations, fast degradation, and efficient biogenic properties. The authors also recommended the use of hexacyanoferrate metal, ZnO, and $TiO_2$ for the removal of PAHs from the environment.

Mahgoub [66] did a review of the utilization of PAH extraction from the environment using nanoparticles. The authors listed some commonly used nanoparticles (magnetized and magnetic NPs, metal oxides, metals, and mesoporous silica) in the sorption of PAHs in environmental media. These nanomaterials are applied in many sectors like in a space ship as fuel additives, optics, mechanics, feed and food, biomedical, pharmaceutical as a drug delivery tool, the environment, and health industries. This is because NPs have high sorption and surface area capacities. The successful application of NPs in the decontamination of PAHs on different matrices was highlighted and discussed. Some problems of the adsorbent benefits of NPs of PAHs like their fate and disposal were pointed out. However, some biological, green, and nonhazardous techniques were recommended by the authors that will improve the affinity and removal efficiency of PAHs. This will avert protracted exposure of nanomaterial on the environment and humans. The incidences of health risks on the brain, lungs, and skin will be eliminated by the introduction of these eco-friendly NPs.

### 6.3.3 Heavily Polluted Soil with Heavy Metals

Mohamed et al. [67] tested and evaluated the application of NPs in the elimination of heavy metals in the soils. The authors stated that nanotechnology is a novel technology that offers a variety of benefits like highly effective immobilization of pollutants converting them to less toxic forms as it is a cheap technology. Nanocarbon (NanoC), nanoalginite, nanoZVI bentonite, nanoZVI, and nanovalentFe are potential nanomaterials that can be applied for the potential immobilization and sorption of heavy metals like Pb and Cd in contaminated soils. These nanomaterials are produced ex situ using bottom-up and top-down techniques. Thereafter, the transmission electron microscope (TEM) was used to characterize them. The results from the nanocharacterization showed that the cation capacity exchange, surface area, and particle sizes were observed to be 42.5–47.7 cmolc/kg, 194.2–259.7 $m^2/g$, and $< 70$ nm correspondingly. The capacity of adsorption for Cd (17,850–25,970 mg/kg) and Pb (37,450–93,450 mg/kg) was observed to be high as well as the adsorbate retention potential. Also, a small percentage of Cd (10.8%–33.4%) and Pb (13.7%–35.6%) were desorbed, respectively, exempting that of the nanoC. The examined nanoparticles showed high efficacy in the immobilization of Pb and Cd in contaminated soils. The plant treated with nanomaterials via diethylenetriaminepentaacetic acid (DTPA) extraction of Cd and Pb from it showed a reduction in Pb and Cd concentration at 2.88 and 0.06 mg/kg, respectively. The findings from the study showed that nanoC is an effective pollutant cleanser, and it is recommended for soil reclamation of heavily polluted metals.

The influence of toxic metals in the aquatic environment has been long-fingered for their negative impacts on the resources therein. However, there is a clarion call to address this environmental menace. On this note, Yang et al. [68] did a review of the elimination of toxic metals from sewer water utilizing nanoparticles. The authors stated that the removal of metal contaminants in wastewater is geared toward sustainable management of the ecosystem. In recent times, various types of technologies have been employed in the elimination of heavy metal from effluents. However, they have been spotted to be ineffective and also capable of generating additional wastes during the process. A novel technology that involves the use of nanomaterials that have been proven to be green, sustainable, nontoxic, eco-friendly, and cheap can be used to substitute these traditional methods. This new technology can be used to remove heavy metal from polluted water because of the nanometer effects it possesses. Examples of these nanomaterials are nanocomposites, metal oxides, zerovalent metal, and nanocarbon. They stated that given the benefits of nanomaterials in the utilization for environmental cleaning of heavily polluted environments, especially heavy metal from wastewater, a comprehensive nanotechnique should be considered in the reduction of cost of production, their synthesis, separation, reusability, and capability of the process. This will reduce the impact and risk of the fate of nanomaterials in the ecosystem. In conclusion, the application in the environmental and health sectors, advantages, and limitations, as well as their future potentials, were discussed.

Baragaño et al. [69] tested and evaluated the environmental elimination of heavy metals like P, As, Cd, Pb, and Cu using graphene oxide nanomaterials (nGOx) as related to its counterpart zerovalent iron nanoparticles (nZVI). The nanoparticles were identified by microscopy (atomic force), dynamic light scattering, CHNS-O examination, and X-ray methods. Samples of soils were treated with nGOx and nZVI to determine the ability of the materials to immobilize and break down pollutants of concentration range 0.2%, 1.0%, and 5%. It was noticed that nGOx immobilized efficiently Cd, Pb, and Cu but mobilized P and As at both high and low concentrations, respectively. On the other hand, nZVI indorsed prominent immobilization outcome for Pb and As, a lesser outcome for Cd, and elicited the accessibility for Cu. The soil electrical conductivity and pH have been affected slightly by nGOx. In general, nGOx appears as an effective immobilization and/or mobilization option for the nanobreakdown of soil pollutants if combined with other methods of bioremediation.

Medina-Pérez et al. [70] did a review of the use of nanoparticles in the cleanup of contaminated soil with metals. The authors stated that nanomaterials are generally developed for use by humans in the industrial sector to combat by-products and waste chemicals generated in the environment. Of recent, the management of adulterated soils using nanomaterials has become an evolving remediation technique in modern times to enhance the performance of environmental sustainability. However, there has been serious concern about the use of this technology on human health and the environment as the fate of the wastes released cannot be trusted. Be that as it may, nanotechnology has immense benefits in the removal of toxic wastes from soils like metals when compared to the traditional methods. They recommended that this technology should be standardized and evaluated by decision-makers and scientists for effective deployment in large-scale use while considering the social well-being, health, and environmental fitness.

Zand et al. [71] tested and evaluated the coapplication of titanium dioxide nanomaterials ($TiO_2$ NMs) and biochar to enhance remediation of antimony (Sb) from the soil via uptake and flora response of Sorghum bicolor (millet). The millet seedlings were exposed to the varying concentrations: 0, 100, 250, and 500 mg/kg of titanium dioxide nanomaterials and 0%, 2.5%, and 5% of biochar concentration to ascertain the influence of flora growth on the physiological retort, accumulation, and absorption to Sb in polluted soil. The combined application of the biochar and the $TiO_2$ NMs demonstrated a positive influence on the tested plant and established growth in the polluted soil. It was noticed that an ample amount of Sb was found in the shoots of the plant when related to the roots of the same plant in all the treated groups. The use of the biochar elicited Sb immobilization in the soil. However, the utilization of the titanium dioxide nanomaterials significantly improved the ability of the tested plant for Sb with the highest accumulation size (1624.1 μg) in each pot attained in 250 mg/kg titanium dioxide nanomaterials per 2.5% biochar treatment. The association of the biochar and the $TiO_2$ NMs significantly enhanced the chlorophyll contents of the tested plant (S. bicolor) when related to the titanium dioxide nanomaterial treatment and amendments. The findings of the study presented a novel method of combined utilization of the biochar and the titanium dioxide nanomaterials in the flora remediation of antimony in polluted soils, which is an intelligent collaborated technique for future application of heavy metal remediation in different environmental settings.

Haijiao et al. [72] in a review examined the treatment of wastewater polluted with excessive Zn, Fe, and Ag by using nanomaterials. They stated that nanomaterials such as zerovalent metal nanomaterials have been used to improve the adsorption and catalysis properties of metals in a polluted environment in recent decades. They opined that studies have shown the effectiveness of the elimination of contaminants from sewer water by the treatment techniques of nanomaterials. They stressed the benefits gained in the use of iron oxides, nanocomposites, carbon nanotubes, ZnO, and $TiO_2$ in the cleanup of the polluted environment with excessive ZN, Fe, and Ag contaminants. However, there are worries about the potential toxicity nanomaterials portend in the extensive use. Nonetheless, there is also a paucity of insufficient standards for the evaluation of the toxicity potentials of nanomaterials. So, an all-inclusive comparison and evaluation of nanoparticle toxicity are urgently needed to safeguard their actual applications. Thus, the evaluation of the performance mode of action of nanoparticles in wastewater and water cleanup should be looked upon in subsequent researches and investigations in different sectors of usage.

## 6.4 APPLICATION OF NANOMATERIALS IN AGRICULTURE

The agricultural field is very vast, and the nanomaterials have a great potential application (Figure 6.4) in this domain for enhancing the crop yield, stress tolerance, anti-pesticidal activity, etc.

### 6.4.1 Nanomaterials as Seed Enhancers/Growth Stimulator

Nanotechnology has proven to be a very effective means of promoting food safety by the enhancement of crop growth and production, thereby enabling sustainable agriculture. Nanomaterials that are used as fertilizers in agriculture possess some physicochemical characteristics, which are known to significantly increase the metabolism of plants. Boutchuen et al. [73] investigated the use of low and high concentrations of hematite nanoparticle fertilizer on the growth and final yield of four various leguminous plants: mung bean (*Vigna radiata*), chickpea (*Cicer arietinum*), red beans, and black (*Phaseolus vulgaris*), using the modified seed presoaked method. They recorded a 230%–830% significant improvement in the growth of all legumes with

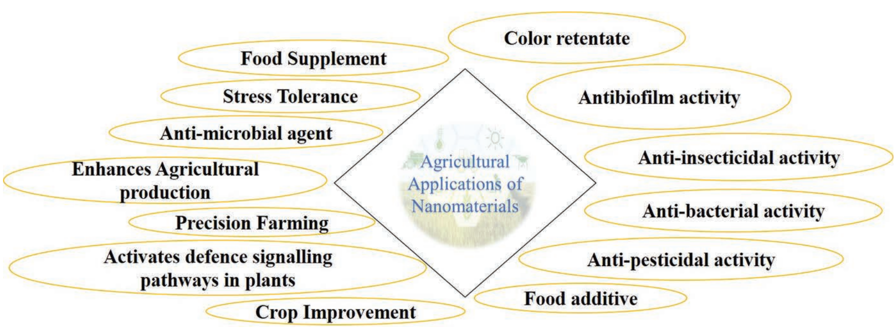


**FIGURE 6.4** Potential applications of nanomaterials in the agricultural field.

the mung bean having the maximum growth impact. It was concluded that hematite nanofertilizers are a promising nanotechnology approach for sustainable agricultural development with low levels of environmental toxicity on the soil physiology. Janmohammadi and Sabaghnia [74] soaked seeds of sunflower (Helianthus annuus) before sowing in various concentrations of 0, 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2 mM of nanosilicon solutions for 8 h. The result obtained indicated that at a minimal concentration of 0.2–0.4 mM, there was a significant upsurge in the germination rate of the seeds by 50% and enhanced root length and also a better seed potency. Ghazal et al. [75] tested the capability of biomass and secondary metabolite production of *Stevia rebaudiana* by immersing metallic alloys of gold(Au) and copper(Cu) into root cultures of the plant. When 30 μg/L of nanoparticles was added to the root cultures, there was an increase in biomass production on the 27th day of the experiment. The authors also recorded a significant increase in phenolic and flavonoid production, both of which had a direct correlation to dry biomass.

Carbon nanotubes have been shown to aid seed sprouting and development of *Solanum lycopersicum* (tomato) by improving the water absorbance by the plant [76]. Pandey et al. [77] investigated the biomass production and germination rate of switchgrass and sorghum using multiwalled carbon nanotubes and graphene. They recorded an increase in the rate of germination of switchgrass by 28% when compared with the control and also prompt germination of sorghum. Carbon-based nanoparticles were also reported to increase salt stress tolerance when NaCl was added to the medium of growth. It was concluded that carbon-based nanoparticles are key to sustainable agriculture. Also, Nair et al. [78] inspected the influence of the dimension of C60, carbon nanotubes, and graphene on the sprouting of rice seeds. It was revealed that carbon nanotubes significantly increased the sprouting rate of rice seeds. Thus, it was recorded that there was an increase in moisture content at the sprouting time of the seeds treated with carbon nanomaterials. The authors reported healthier plants with well-established roots, which showed the effect of a more advanced seedling when previously sprouted seeds were grown in a basal medium containing carbon nanomaterial. They concluded that carbon nanomaterials are good development boosters of rice seedling. Juhel et al. [79] assessed the biological impact of alumina nanoparticles ($Al_2O_3$) on the photosynthesis, development, and morphology of *Lemna minor*. They discovered a considerable improvement in the biomass with an increase in alumina concentration. It was reported that the mechanism involved in the use of alumina nanoparticles in *Lemna minor* is novel and is known for its enhancement of photosynthesis in the weed.

Li et al. [80] compared the influence of different concentrations of 20 mL nanoscale zerovalent iron (NZVI) (10–320 μmol) and a single concentration of 20 mL of ethylene diamine tetraacetate-iron (EDTA-Fe) solution (40 μmol/L), for its stimulation ability on the germination and subsequent growth of peanut (*Arachis hypogaea*) seedlings. They discovered that at a low concentration of 40 μmol/L NZVI, there was an early seed sprout and a longer stem length when compared to 40 μmol/L EDTA-Fe solution. TEM showing the cotyledon of *Arachis hypogaea* treated by NZVI revealed that NZVI can loosen and open the seed coat, and this, in turn, aids the intake of water helping early germination. They also recorded that at higher concentrations of 300–320 μmol/L, NZVI was lethal to *Arachis hypogaea* seedlings. The use and importance of silicon nanoparticles as pesticides have been studied and emphasized [81–83]. Rouhani et al. [84] discovered that $SiO_2$ nanoparticles were toxic to the adult and larvae stage of cowpea seed beetle at 100% and 83%, respectively, and therefore could be used in the control of *Callosobruchus maculatus* agricultural pest.

### 6.4.2 Nanomaterials as Biopesticide

Among the current development in agricultural innovative science, nanoparticles play a crucial part in protecting crops due to their exceptional physical and chemical features. Nanoparticles attach themselves to the membrane of pathogenic microbes, thereby causing damage/death due to its high rate of transfer of energy [85]. Viruses, insects, bacteria, pests, and fungi were identified to infect, lessen yield, and quality of farm produce. Researchers stated that the use of silver NPs has significantly caused the suppression of pathogenic diseases in the agricultural sector. Nanomanipulation of nanosized particles with fluconazole was effective in protecting *Trichoderma* sp, *P. glomerata*, and *C. albicans* [86]. Zinc oxide was discovered to lower the number of cells in *S. typhimurium* and *Staphylococcus aureus* to the barest minimum within 4–8 h of administration [87]. They reported that Ag NPs, Ti $O_2$, and Au NPs helped in protecting protein synthesis by bacteria, protecting tobacco plants from *Vibrio harveyi,* pathogen, and the NPs act on *E. coli* by reducing ATPase action, thus disrupting the adenosine triphosphate (ATP) activity at the membrane level [88,89]. Utilizing conventional pesticides as well as herbicides has been limited, due to the problem of resistance and biological diversity in the soil resulting in the biological accumulation of pesticides and herbicides in the soil with the resultant soil pathophysiology [90]. The work of Nair et al. [91] revealed the inhibitory potential of Ag nanoparticles against some fungi species that resulted in the death of oak trees. Indicating that nanoencapsulated pesticides are easily taken up through the surface of plants, this assists in the extended-release period of active agents compared to commercially produced pesticides that could be easily washed off by rain [92]. Thus, using conventional chemicals could cause a grievous adverse effect on both the human and immediate environment [93].

Nanoparticles help to improve the dissolution of partially soluble crucial ingredients and help in discharging the useful ingredients gradually to the plants. Chitosan-derived NPs embedded with some amino groups and complexes of commercial pesticides showed that incorporating commercial pesticides (rotenone) into NPs was amplified to 13,000 times powerful when compared to the single use of rotenone [94,95]. Nanomaterials impregnated with essential oil from garlic were found to be very effective against *T. castaneum* (Herbst) [96]. Aluminosilicate in nanotube can glue to the surface of plants applied, whereby the active components in the nanotube possess the capacity to glue to the hairs of the insect pest surface and diffuse into their body to cause physiological disruption and damage [97–99]. Nanoparticles give a wider range of effectiveness in the agricultural application when compared to other chemicals, owing to the enormous superficial area, quick mass transmission, and easy attachment to the target area of the plant [87]. They can let out important complexes to the plants due to the presence of a modified control system when compared to the conventional type of pesticides. The presence of the control transport system has made it easy for the release of active component to the plant and also to meet the targeted site for the expected period of time, thereby proving effective control against insects and pests [100], increasing solubility, the dispersal of dissolved fat in water [101], enhancing biological effectiveness, lowering the toxicity that would have been caused by the application of normal pesticides on plants, removal of organic diluents, and amplified effectiveness [102].

The use of nanotechnology has reduced the dosage of conventional pesticides to just the needed components to reach the target sites. Through nanoencapsulation, insecticides are gradually effectively released in a regulated pattern to control the damage usually caused by pests and insects. Nanoformulation has been found to possess various advantages over conventional pesticides owing to its great target distribution and modified mechanism of release. Also, the dosage needed to exhibit a pesticide action is very minimal, thereby limiting the rate of resistance by plants to the nanomaterials and the environmentally friendly nature [68]. Nanocrystalline oxides of metals are greatly used for broad-spectrum pesticides. Metals like ferric oxides, aluminum oxides, cerium oxide, titanium oxides, and Mg oxides are very efficient [59]. They are applied owing to their greater rate of adsorption, quick migration due to higher definite surface area, and superior amount of reaction on the surface compared to those conventional pesticides [103–107]. These NPs also help to convert hazardous chemicals into forms that are eco-friendly and help to reduce the issue of toxicity [108].

Elbeshely et al. [109] carried out a study by spraying Faba beans plants already infected with the mosaic virus with various concentrations of AgNPs and discovered that significant change was recorded within 24 h and thus suggested that silver NPs possess insecticidal activity. The administration of poly detached AuNPs was found to suppress mosaic virus on the barley plant, thereby bringing about resistance development in the barley plant [89]. Studies have shown that chitosan could induce some level of protection on different plants against viral infections. It controls the rot in the roots of the tomato plant, in grapes, in a bunch of Botrytis and *P. grisea* in rice plant [110,111]. Solid lipid NPs make available the medium to trap lipid-linked active materials without utilizing carbon-based solvents [112,113].

Insecticides that possess a reduced ability to dissolve in the presence of aqueous need carbon-based solvents to assist in the proper dissolution of the pesticides/insecticides leading to reduced toxicity of the insecticides [114]. Thus, nanoparticles could be utilized in increasing the rate of solvent and also to reduce the degree to which the insecticides could become toxic [115]. Rani et al. [116] preserved castor leaves with encapsulated silica NPs scattered in acetone. The authors stated that *S. litura* and leaves of castor plant possess reduced feeding potential, resulting in death owing to malnourishment; thus, it was concluded from these studies that NPs-encapsulated active components improved the issues of instability [117]. Nanotechnology has greatly helped in the agricultural and food industry, like helping in plant growth, production, and yield [118]. Nanotechnology has also assisted the environment to renew itself and to manage some wastes that would have constituted environmental hazards [119]. The implementation and adoption of nanotechnology have also helped in the reduction of toxic chemicals on farm products [120,121]. Agriculturally produced bionanocomplexes have been applied to upgrade production and eradicate microorganisms causing diseases in plants [122]. During their research, El-Benday and El-Helaly [81] found out that silica nanoparticles could be effectively used as plant pesticides. The administration of nanosilica particles in the larva of *Spodoptera littoralis* showed great lethal potency at all the administered concentrations [123].

The antimicrobial potency of several nanoparticles, mostly copper and silver NP, has been assayed against different types of microorganisms causing plant diseases. Cioffi et al. [124] revealed the antifungal effectiveness of polymer-NPs in agriculture particularly on farm produce, thus bringing about greater water and nutrient administration and retention. Nanotechnology has also been helpful in the areas of plant production and the transfer of genetic materials [120]. Park et al. [125] assayed the potency of silica-NPs in controlling plant pathogens such as *Botrytis cinerea, Colletotrichum gloeosporioides*, *Pythium ultimum*, and *Rhizoctonia solani.* This was done in others to conquer the parasitic disease in pumpkin by spraying the NPs on the contaminated leaves for about 3 days; upon this, there were positive results in the eradication of the pathogen. Kim et al. [126] conducted a study on the fungus causing disease state in oak trees (*Raffaelea* sp.); this fungus sometimes causes mortality and stunts the development of the oak trees. These NPs were very effective in stopping the activity of the fungus. There was also another discovery on the elimination of the activity of some fungi such as *Phoma and Fusarium* [127]. The use of NPs as pesticides, herbicides, and insecticides has widely been part of people involved in agricultural business and in others to help their yield and possible maximum production [128]. There has been an improvement in the production of agro-friendly material with the utilization of NPs, thus assisting in breaking down some solvents much more than those that existed before NPs. The majority of farmers have utilized several suspensions of nanosized materials, either the oil- or water-based ones comprising of accurate pesticides or herbicides materials in them, which have been used in the treatment and/or preservation during postharvest [87].

Nanoparticles have been used to transport DNA and some important chemical agent into tissues of the plant in others to secure the plants from plant pathogens [2012]. Permeable silica NPs could be loaded with validamycin and used in the production of liquid pesticides. This formulation had quick actions on the elimination of plant pathogen [129]. Oil–water nanosuspensions were a great formulation viable against insects and pests while farming [130]. Nanosilica was found to have an outstanding nanoparticle, gotten from silica. It was used for various applications in liquid treatment and prophylactic application. Lately, researchers discovered nanoparticles to be beneficial as a catalyst and as nanopesticides [123]. Researchers investigated the application of nanosilica as pesticides and found out that the effectiveness of nanosilica depends on the form/manner in which the pests utilize the collection of lipids found in their cuticle for confirming the lethal state of pest via dryness [89]. Studies revealed the insecticidal efficacy of polyethylene glycol coated with nanomaterials seeded with garlic used against the growth of *Tribolium castaneum*; this nanoformulation was found to have 80% effectiveness against the insect [131].

During their work, they performed bioexamination where they set up the liquid formulation of an aqueous suspension of NPs, applied the technique on rice, and kept it under observation for 7 days. A great result was recorded of the mortality of rice weevil upon application of NPs on the grasserie infection from silkworm; there was a great reduction in the viral load of the leaves treated with the ethanol suspension of the NPs aluminum silicate. There was an investigation on the insecticidal effectiveness of nanoaluminum against *Sitophilus oryzae* and *R. dominica,* which were known to cause the largest percentage of spoilage harvested crops worldwide. There was a substantial lethal rate after 3 days observation of nanocapsulated alumina when infected wheat plants were treated with it, the result obtained when compared with economically available insecticides, showed that nanocapsulated alumina brought about some promising advances to the world as a pest control agent. Zhang et al. [138] reported that wings of cicada found from insects were gotten from a field and were discovered to structure the pillars of nanomaterials. The cicada used the light-shiny features of the nanoparticles to elude the effect of predators [132]. They then concluded that nanotechnology has a great deal to contribute to the agricultural world [131].

Different studies have investigated *Talaromyces flavus* isolated from strawberry in others to determine their inhibitory potency. *Glomerella cingulata* is known to cause anthracnose and *C. acutatum* in plant nursery [133]. There was a great reduction in the disease-infected plant after the administration of the modified strains. Nanotechnology has been able to add more value to the development of biological pesticides that are not toxic to plants, humans, and the environment [134]. Studies have revealed that utilizing nanomaterial in preventing *Azadirachta indica* oil from quick dilapidation, provides plant's lasting protection against pest [134]. This technology has been so helpful in improving the sustainability and efficacy of natural produce [135]. It also provides measured molecules at the site of the target, reduces toxicity effects, and avoids digestion of the active compounds by microbes [135,121].

Studies have examined and highlighted different experiments done on the use of NPs as nanofungicides; this was done by integrating the fungicides in solid woods [136]. Several fungal isolates were utilized in determining the effectiveness of the nanofungicides. The results obtained from the investigation showed a reduced level of evaporation of the NPs at ambient temperature, enhanced stability, and increased rate of stability [137]. The experimental work of Damalas and Koutroubas [138] explained that the use of synthetic insecticides could lead to resistance of pests to the applied pesticides while trying to manage *Oleander aphid* [139]. Their study revealed the biological assay of that insecticidal potency of Ag-Zn nanomaterials on *A*. Merrie and thus concluded that it could be very efficient as an agent that controls pest [140].

## 6.5 CONCLUSION AND FUTURE RECOMMENDATIONS

This chapter has provided detailed information on the various types of nanomaterials in resolving several challenges encountered in the environmental, agricultural, and biomedical fields.

Therefore, there is a need to search for novel nanomaterial that could be applied in future functional research and development of all the highlighted sectors above. Also, there is a need to intensify more effort in the utilization of natural or biological nanomaterials that could be commercialized as well as that could be patented. Moreover, there is a need for the government, stakeholders, and scientists to integrate and encourage the study of nanotechnology into various education systems most especially in developing countries.

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