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Applications of Metal Nanoparticles in the Agri-Food sector

Vijay Devra

Address:

Janki Devi Bajaj Government Girls college Kota (324001) Rajasthan, India

* Corresponding author:, ***Vijay Devra:*** v_devra1@rediffmail.com

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ABSTRACT

The application of smart and active packaging, nano sensors, nano pesticides, and nano fertilizers, as well as the rapid development of nanotechnology, has expedited the transformations of traditional food and agriculture industries. Metal nanoparticles have been produced for a variety of applications, including food quality and safety, crop development, and environmental monitoring. The most challenging issues and potential opportunities in the food and agriculture sectors are discussed in this chapter, as well as the most recent trends in nanotechnology from research findings. We focused on the possibilities for biosynthesized and bio-inspired nanoparticles to be used in sustainable development. Nanotechnology is used in agriculture to provide agrochemicals and nutrition, as well as insecticides, nano-scale carriers, smart packing, nanosensors, and nutritional deficiency monitoring. Nanomaterials have a broad range of applications in the food industry, including production, storage, packaging, bioavailability, nutrient conductivity, and food safety. Nanomaterials are likely to become more widely used in agriculture in the future, increasing human and environmental exposure to these materials.

Keywords: Nanotechnology, Nanomaterials, Metal nanoparticles, Applications, Agri-food sector

INTRODUCTION

Nanotechnology is concerned with nanoparticles with at least one dimension of 1 to 100 nanometers. Nanotechnology has a wide range of applications, and synthesizing functional nanomaterials for Agri-food applications from biogenic resources is universally recognized as a sustainable, human- and animal-safe approach. (Sampathkumar and colleagues, 2020). With the advent of equipment to monitor and analyze nanomaterials, they have infiltrated every part of human existence, starting with fabrics (Rivero *et al.,* 2015) and progressing to more serious uses in the agri-food, vehicle, biomedical, and wastewater industries. Nanoparticle application and utilization provide superior qualities not seen at larger size scales, and with the emergence of nanotechnology, this is becoming more ubiquitous (Global Industry Analysts Inc., 2019). With a rapidly growing global population, it is projected that food demand will skyrocket, putting enormous strain on the agri-food business. (Adisa *et al.,* 2019) Nanotechnology has been employed in food processing and preservation, crop productivity, animal feeding, and environmental monitoring since 2003 when it was first introduced into the agricultural and food industries (He *et al.,* 2019).

Biosynthesized nanoparticles offer immense potential in green technology for enhancing the quality of life through applications in the Food and Agriculture fields such as improved food quality and safety, reduced agricultural inputs, and improved nanoscale nutrient absorption from the soil. Agriculture, a smart delivery system for agrochemicals such as fertilizers and pesticides, early detection of diseases in food materials, system integration for food processing, packaging, monitoring, and natural reservoir management all have growth potential. (Ali *et al.,* 2021; Rawat *et al.,* 2018). All of these factors have an impact on the production of food and agricultural-based products, which are key driving factors. This nanomaterial is expected to become an important agenda item in the not-too-distant future, with significant benefits for consumers, producers, farmers, ecosystems, and society (Kaphle *et al.,* 2018; Baker *et al.,* 2017). Scientists and professionals are looking for alternate, environmentally safe, and intensive approaches to control plant diseases (Parthiban *et al.,* 2019). Metal nanoparticles as antimicrobial elements have grown increasingly popular as a substitute for chemical pesticides, thanks to technological advancements that have made their products more cost-effective (Malandrakis *et al.,* 2019; Sahadan *et al.,* 2019). Nanotechnology's new role as a precision agriculture technique should boost crop yields while lowering leaching and emissions (Duhan *et al.,* 2017). Nanoparticles for the controlled release of nutrients, insecticides, fertilizers, and other uses have been appraised as a positive influence of nanotechnology in the agri-food business (Yata *et al.,* 2018; Rawat *et al.,* 2018; Singh *et al.,* 2019).

Metal/Metal oxide nanoparticles offer unique features that make it easier to produce durable and multifunctional materials for a variety of applications. Because of their unique properties that improve adsorption by plants, disease management, and pathogen detection metal nanoparticles have the potential to transform the food and agriculture industries (Abd-Elsalam *et al.,* 2021). Nanoparticles have a unique surface and characteristics due to their unique design. Metal oxide nanoparticles, magnetic nanoparticles, gold nanoparticles, mesoporous silica nanoparticles, quantum dots, and carbon nanomaterials have all been made (Wang *et al.,* 2016 a). Metal oxide nanoparticles, such as copper, gold, silver, aluminum, zinc oxide, and titanium oxide, have gotten a lot of interest in recent studies as prospective alternatives to chemical antimicrobials. Different metal nanoparticles can inactivate a wide variety of Gram-negative and Gram-positive bacteria, filamentous and unicellular fungus, algae, protozoa, and viruses (Luksiene, 2017). Nanoparticle application is still a new and novel technique that requires further research and study to properly understand and apply their properties for the enhancement of food, crops, and other fields of science (Pestovsky and Antonia, 2017). Because there is a growing interest in using biogenic nanoparticles in the agri-food industry, the goal of this review is to provide an overview of biogenic nanoparticle applications in the agricultural and food industries. Encapsulation methods are commonly used in agri-food applications to protect active elements by minimizing interactions between the encapsulates and the environment, either through a coating or a matrix material (Sinha *et al.,* 2019: Badawy *et al.,* 2022). The present review discussed metal nanoparticles applications in agri-food sector.

Agricultural Applications:

Nanotechnology's emergence has transformed the scientific world due to its novelty, rapid growth, and broad applications. Nanotechnology's use in agriculture has grown in recent years, especially inaccurate delivery applications (Abd-Elsalam, 2020). The major goal of employing nanoparticles in agriculture is to boost agricultural yields by using nanosensors, nano pesticides, and nano fertilizers to effectively manage pests and fertilize crops (Prasad *et al.,* 2017). Although nano-enabled herbicides, insecticides, and sensors are still in the early stages of development, a few commercial solutions that contain nanoparticles of nutrients for plant growth are accessible (He *et al.,* 2019). Nanotechnology is used in agriculture to improve food production by increasing nutritional value, quality, and safety. The most important techniques to improve agricultural production are to employ fertilizers, insecticides, herbicides, and plant growth regulators effectively. The use of nanocarriers facilitates the controlled release of insecticides, herbicides, and plant growth regulators. Because of their inherent toxicity, metal oxide nanoparticles such as ZnO, TiO_2, and CuO have been extensively explored to protect plants from pathogen infestations. Microbes such as *Fusarium graminearum, Aspergillus flavus, Aspergillus niger, Aspergillus fumigatus,* and *Fusarium exosporium* can be successfully inhibited by ZnO NPs, which have strong antifungal and antibacterial action (Dimkpa *et al.,* 2013; Rajiv *et al.,* 2013). Low nutrient absorption efficiency and large losses plague conventional fertilizers. Nano fertilizer development offers a unique alternative to such economic losses. Nano fertilizers can help crops and soil microorganisms absorb more nutrients by minimizing nutrient loss and improving nutrient absorption. (Dimkpa *et al.,* 2018).

The Mechanism for Nanoparticles Interaction In Plants:

Plant transport pathways are important for allowing nanoparticles to infiltrate the plant and surrounding environment, where they can proliferate. Protoplasts, plants, and organs were all used to transmit nanoparticles (Wang *et al.,* 2016 a). The ability of nanoparticles to enter plant cells is mostly determined by the plant species and nanoparticle characteristics and is obstructed by the cell wall (Singh *et al.,* 2015). Nanoparticles enter a plant cell by an active transport process that is controlled by many cellular processes (Tripathi *et al.,* 2017). Dissolution is primarily concerned with the modification of metal nanoparticles, which changes their characteristics and fate in various plant species. In the soil, metal nanoparticles with changing valences undergo redox reactions, transforming these particles through their interaction with biogenic redox reactions in plants (Rico *et al.,* 2015). The significant applications of nanoparticles in agriculture are discussed below (Fig. 1).

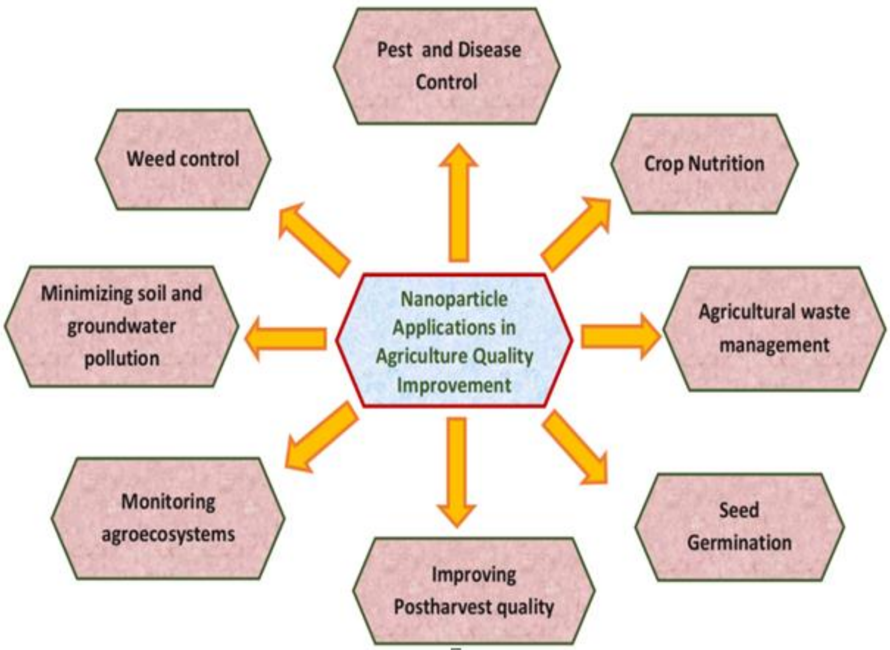

Fig. 1. Nanoparticle Applications in Agriculture Quality Improvement

Crop Nutrition:

Nanoparticle-based fertilizers require an appropriate substrate to spread the nanomaterials across agricultural areas (Kumar *et al.,* 2018). Nano fertilizers are nano formulations of fertilizers like nitrogen, phosphorus, and potassium, as well as other critical minerals and micronutrients. The major goal of these formulations is to achieve the goals of reducing element evaporation, increasing nutrient uptake, reducing fertilizer dose, and improving micro soil flora and fauna as well as water holding capacity. Encapsulation of nonporous material, polymer coating surrounding fertilizer, and nutrients themselves in nano form can all be used to administer fertilizer via nanoparticles (Madhavi *et al.,* 2016) Furthermore, nitrogen release can aid in the reduction of land and water pollution as well as the protection of plants from a variety of abiotic and biotic stresses (Singh *et al.,* 2017). Soil-applied nano fertilizers can improve nutrient release and penetration into roots, resulting in improved plant absorption and translocation. Foliar spray nano fertilizers, on the other hand, boost plant development by increasing chlorophyll synthesis and dry matter production. As a result, plant growth has improved (Dhokev *et al.,* 2013). A nanoparticle with stronger phloem translocation capacity is more likely to have better plant dissemination. As previously said, nanoparticles' main characteristics are their enhanced surface area and quantum effects, which allow for easier absorption and future distribution of nutrients. Nanoparticle size also influenced competitive binding with receptors and the reduction of reactive oxygen species. Nano fertilizers with iron chelated chelates enhanced photosynthesis, adsorption, and surface area of leaves (Singh *et al.,* 2015)

Nanostructured fertilizers can improve the efficiency of plant nutrition applications by being target-oriented and releasing nutrients at a controlled rate. Nano fertilizers, on the other hand, have been supposed to be able to reduce plant disease and improve seed germination, seedling growth, nitrogen metabolism, protein synthesis, and product quality (Shinde *et al.,* 2020; Hussein *et al.,* 2019). Fertilizers based on nanoparticles and nano encapsulated fertilizers have been demonstrated to improve plant development by promoting the release of nutrients to the plant (Nair *et al.,* 2010). Nano fertilizers also help to improve soil fertility and remove waterlogging pollutants (Giraldo *et al.,* 2014). Pearl millet crop output was improved with the use of zinc nano fertilizer (Tarafdar *et al.,* 2014) ZnO NPs, with a diameter of 25 nm and a concentration of 1000 ppm, were used to boost seed germination and seedling vigor, as well as lower leaf chlorophyll content (Prasad *et al.,* 2012). In investigations on the effect of ZnO NPs on onion, the plants grew faster and flowered 12 to 14 days earlier than the control plants (Laware and Raskar, 2014). Because comparable NPs may be utilized to coat zinc for dispersion, micronutrient zinc is being employed as zinc coating manure. (Rameshaiah *et al.,* 2015). The usage of ZnO, FeO, CuO, and TiO2 NPs in association with appropriate biofertilizers was found to improve plant photosynthetic ability and antioxidant enzyme activity, resulting in increased crop growth and yield components (Timmusk *et al.,* 2018; Anderson *et al.,* 2017). Researchers discovered that NPs and biofertilizers improved the physiological state and vegetative growth indices of crop plants by increasing quality and yield characteristics (Jacobson *et al.,* 2018; Shcherbakova *et al.,* 2017) (Table 2)**.**

Seed Germination:

Nanoemulsions of chemicals have been reported to significantly affect seed germination and crop plant growth. The utility of nanoformulations of plant growth, promoting substance in the form of Nanoemulsions, along with nano fertilizers, improve the rate of germination, influence cracking seed inactivity, and improve seedling robustness. Many nanoparticles have been used to improve seed germination and plant growth, including Ag (Alumtairi and Alharbi, 2015), FeS2, ZnO, and CO nanoparticles (Hoe *et al.,* 2018). Nanoparticles have been shown to penetrate the seed coat and improve seed germination by increasing water absorption, enzyme levels, antioxidant systems, and lowering oxidative stress caused by H_2O_2 and superoxide radicals. The impact of metal nanoparticles on the growth and metabolic functions of plants, depending on the plant species and their impact on plant growth and development. Diverse metal nanoparticles have been used as pretreatment agents to wheat (Taran *et al.,* 2017; Jhanzab *et al.,* 2019), corn (Mahakham *et al.,* 2016), and spinach (Srivastava *et al.,* 2014) seeds to enhance seed germination, growth, and stress tolerance in various studies. (Mahakham *et al.,* 2017). reported the future of nanotechnology for sustainable agriculture and seed industry by inducing seed germination and starch mobilization in rice using biogenic AgNPs. Plant development and germination are affected by abiotic stress factors. TiO_2 NPs can be utilized to avoid wheat seed germination problems and cadmium stress in plant growth (Faraji and Sepehri, 2018; Yasmeen *et al.,* 2017) found that uptake of biosynthesized copper and iron from onion extract increased wheat yield through physiological effects. Z. mays seeds treated with Mg $(OH)_2$ NPs revealed a considerable increase in germination rate (Shinde *et al.,* 2020).

Furthermore, these fungus-derived green nanoparticles showed outstanding action in terms of increasing percentage and breaking seed dormancy. Mg $(OH)_2$ NPs could be used to boost the growth of the Z. Mays plant in the fields. In comparison to untreated plants, the chlorophyll fluorescence investigation indicated that Nanoparticles treated plants have a high-performance index. Overall, the results showed that metal nanoparticle treatment could easily enter and translocate in various plant sections, resulting in enhanced seed germination rates and plant growth promotion. TiO2 NPs are one of the metal oxide nanoparticles that enhances the vigor of aged seeds and the production of chlorophyll. They also increase the reactivity of the rubisco enzyme, which promotes photosynthesis and plant growth (Siddiqui *et al.,* 2015). In comparison to plants that did not have nanoparticles, seed germination in lettuce increased the ratio of the shoot to the root (Nair *et al.,* 2010). Cell division, seed, and pollen germination, and plant growth were all promoted by biosynthesized AuNPs, according to many studies (Thakur *et al.,* 2018).

Pest and Disease Control:

Nano pesticides are pesticides developed at the nanoscale to ensure that the active components are fully utilized for insect and disease control. The usage of AuNPs and iron oxide NPs to manage plant pests has boosted the efficacy of pesticides (Vinutha *et al.,* 2013; Narayanan *et al.,* 2016). Nanoparticles have an important role in the creation of stress-resistant transgenic plants such as *Medici, truncatula, zio mays, Nicotina tabacum*, and *Oryza sativa L.,* as well as the development of defense mechanisms against pathogen-caused disease (Aras *et al.,* 2015). Nanoparticles can be used to protect plants directly, the crop, or nanoparticles as carriers of established pesticides, and can be delivered via spray, soaking into seeds, foliar tissue, or roots. After conducting field trials toward objective (Table 1), Agri nanotechnology can be employed to generate effective formulations for crop plants.

Metal nanoparticles have also been used to transport herbicides, fungicides, insecticides, and other chemicals. Many studies have demonstrated that utilizing Nano pesticides reduces the number of insects in agricultural fields by a significant amount. Biosynthesis of AgNPs *cassia fistula* extract showed substantial efficiency on insect Aedes albopictus and *Culex pipens* pollens, according to (Fouad *et al.,* 2018). CuO, ZnO, and Mn2O3 nanoparticles have antibacterial properties against plant diseases (E. coli) (Kaweeteerawat *et al.,* 2015). Latex from *Jatropha curus* was used to inhibit Aedes aegypti, beetles, and mealy sacks in a triggered trypsin inhibition study (Patil *et al.,* 2016). Furthermore, green synthesized metal nanoparticles have shown favorable results as ovicides and adulticides for many pest species, for example, all larval is instars and pupae of the Cotton Bollworm, *Helicoverpa armigera*, whereby they reveal susceptibility to AgNPs biosynthesized by leaf extract of Euphorbia hirta L. (Devi *et al.,*2014). Similar results were exhibited with larvae of the mosquito *C. quinquefasciatus* and *A. subpictus* exposed to leaf extract of *Mimosa pudica* L. Synthesized AgNPs (Marimuthu *et al.,* 2011). (Suresh *et al.,* 2014) reported biosynthesized AgNPs using root extract of *Delphinium denudatum* wall triggered 100% mortality of second instar larvae of *A. aegypti* L. Greenly produced metal nanoparticles have also shown promise. (Dinesh *et al.,* 2015) found that AgNPs made from aloe Vera (L) Burm.F. leaf extract was harmful to all *A. Stephensi* larvae instars. AgNPs not only had strong toxicity against mosquitoes and ticks, but they also had aduticidal, ovicidal, and ovipositon differences (Benelli *et al.,* 2018). AgNPs made from *Phyllanthus niruri*, for example, were extremely toxic to Aedes aegypti adults (Suresh *et al.,* 2015). In several investigations, biosynthesized NPs against mosquitoes lowered female fecundity, egg hatchability, and decreased longevity (Madhiyazhagan *et al.,* 2015). (Furthermore, Bharani and Namasivayam 2017) observed that AgNPs produced by Punica granted L in *S. litura* third instar larvae altered lipase, invertase, and amylase activities.

Another study found that the accumulation of reactive oxygen species causes DNA damage, ROS-mediated apoptosis, and autophagy in *D. Melanogaster* tissues (Mao *et al.,* 2018) Table 4.4 shows that the fungus's green produced metal nanoparticles have interesting potential for the management of insect pest species (Amerasan *et al.,* 2016). The researchers discovered that fungi such as chrysosporium tropical, J.W. Carmich, *Trichoderma harzianum* Rifai, *Fusarium oxysporum,* and *Cochliobolus lunatus* R.R. Nelson and Hasses developed chemicals that effectively regulated mosquito species (Sundaravadivelan and Padmanabhan, 2014). For the biosynthesis of AuNPs, (Jayaseelan *et al.,* 2013) used an aqueous seed extract of *Abelmaschus esculentus*. They tested the nanoparticles against Candida albicans, Aspergillus niger, *Aspergillus flavus*, and *Puccinia graminis tritci* for antifungal activity. The pathogenic fungus is one of the most significant impediments to agricultural growth, accounting for more than 70% of the crop's yield reduction (Baker *et al.,* 2017). To control the pathogenic fungus, several nanoformulations and metal nanoparticles have been studied. The green synthesis of AgNPs and their application in the control of fungal infections was described by (Rafique *et al.,* 2017). Using a foliar spray of ZnO NPs at 1000 ppm, tomato and eggplant showed promising effects against Fusarium by triggering defense mechanisms in plants (Elmer and White, 2016). A variety of applications are possible for mycogenic NPs, such as nanofertilizers, nanofungicides, plant growth stimulators, and nano-coatings. NPs mediated by Trichoderma have also been used for environmental remediation, including heavy metals contaminant detection and pollution removal (Alghuthaymi et al., 2022).Because the nanoparticles have antibacterial capabilities, research has been done to see if they may be used to protect crops from hazardous microorganisms. The use of CuNPs for the successful elimination of the Xanthomonas Campestre and *Xanthomonas oryzae* pathogens that cause leaf spot and rice blast (Mondal and Mani, 2012) Antibacterial activities of green produced AgNPs have been demonstrated against Erwinia cacticida and Citrobactor Freunde (Paulkumar *et al.,* 2014). Another study discovered that biosynthesized AgNPs are bactericidal against the bacteria *Xanthomonas oxonopodis* and *Ralstonia solanacearum* (Aravinthan *et al.,* 2015). Shawn extracts substantial growth suppression against *Xanthomonas oxonopodis* pv. *buhicae* utilizing biogenic AgNPs produced from *Neptrolepis exaltata* leaves (Bhor *et al.,* 2014). The use of AgNPs produced from microorganisms to detect organophosphate pesticides residues in fruits and vegetables (Malarkodi *et al.,* 2017). Biogenic AuNPs have been claimed to be useful in the management of pests in agriculture and public health (Sundararajan and Kumari, 2017). (Thakur *et al.,* 2018) examined the impact of biosynthesized AuNPs on tomato root-knot nematodes. The nanoparticles had an excellent nematicidal effect and did not harm plant development. According to this research, metal nanoparticles offer a wide range of applications in the eradication of bacterial infections in crops.

Improving Postharvest quality:

Nanotechnology has played an important effect in manufacturing and past harvesting. Controlling microorganisms, packing materials, and other factors improves quality. Nanoparticles for fungus control have been used to extend the life of banana, carrot, tomato, and onion harvests in the past. Because of their physical and chemical stability, availability, and non-toxicity, newer ranges of packing coverages, such as TiO_2 and AgNPs, are used. Nano TiO_2 with light catalytic capability was synthesized, and nano silver with a large surface area demonstrated the ability to absorb and degrade ethylene. Nanoparticles are utilized not even to suppress insects, pests, and disease, but also to improve the quality of cereals, pulses, and fruits and vegetables after harvest. The impact of physiochemically generated metal nanoparticles on the quality of numerous crops, on the other hand, has been well documented. Despite this, there are few publications on the effects of biogenic manufactured metal nanoparticles on historical agricultural harvest quality. Saffron petals are leftovers from the processing of saffron and are discarded after harvesting. (Solgi, 2014) investigated the saffron (Crocus Sativus) peel extract-mediated synthesis of AgNPs and their effect on specific bacteria genera involved in floral reduction and longevity to see whether petal residue could be used for green synthesis. According to characterization data, AgNPs were generated to nanoparticles in less than 30 minutes after intubation, with an absorption peak of 380-400 nm in the UV visible spectrum. Bacillus, pseudomonas, and acinetobacter contaminated the cut flower's preservation solution, and green produced AgNPs were used as an antimicrobial agent. Different quantities of manufactured AgNPs have significantly higher antibacterial activity than pure Saffron petal extracts. Banana biosynthesized AgNPs have antibacterial properties, according to (Bankar *et al.,* 2010). (Kaviya *et al.,* 2011) found that synthesized AgNPs with Citrus Sinensis peel extract had a stronger antibacterial effect on *E. coli, E. aerogenes, Klebsiella sp., and Shigella sp.* (Hassan *et al.,* 2014) investigated the effects of 25, 50, and 100 mg L^{-1} bio-produced AuNPs on rose flower quality, finding that all doses of AgNPs significantly enhanced the life of rose blossoms when compared to the control group. (Solgi, 2018) investigated the effects of AgNPs (25 and 50 mg L-1), thymol (25 and 50 mg L-1), and chitosan (25 and 50 mg L-1) in distilled water and 2% sucrose on cut Carnation Tabor postharvest quality, and found that the vase life of cut carnations was greatly increased. Some microbial-based nanoparticles have been effectively used to improve the quality of various crops.

Weed control:

Weeds are plants that seem to have no place in a cultivated ecosphere of agricultural crop plants that compete for nutrients, water, and sunlight with them. Weeding is a cross-cultural activity in which undesired parasite weeds are manually eliminated. Herbicides are a viable alternative to the time-consuming and labor-intensive weeding process. Nanoencapsulation has been developed to improve herbicide efficiency by promoting controlled release and delivery when sufficiently exposed to moisture (Kumar *et al.,* 2017 b; Amna *et al.,* 2019; Jalil *et al.,* 2020) (Table 1).

Nano herbicides are produced by combining nanoparticles with active chemicals in a mixture. The ability of the compounds, as well as their genotoxicity, was reduced by combining them with nanoparticle-based carriers (Pereira *et al.,* 2014). Herbicides are injected into plants via nanoparticles via tissue and cuticles, and the active material is released consistently and steadily by the nano capsule (Duran and Maezrcato, 2013). AgNPs Shawn synergistic impact with Imazethapyr Simultaneous exposure to AgNPs and herbicides in Arabidopsis thaliana increased Ag concentration in roots, according to (Wen *et al.,*2016). The concentration of amino acids has increased as a result of the exposure of AgNPs in the plant, as has the development of additional Ag+ ions from AgNPs. Microbes, such as viruses, are naturally occurring nanoparticles that have a core and an exterior coating, just as human-made NPs. Bioherbicides were used to suppress the tobacco mid-green mosaic virus, an invasive perennial weed (*Solanum viarum*) of postures, and other non-cropland areas. The NPs were made up of an organosilicon adjuvant and carborundum abrasives, with the carborundum assisting the virus's entrance (Charudattan and Hiebert, 2007; Ferrell *et al.,* 2008).

Monitoring agroecosystems:

Engineering nanomaterials are materials with a diameter of 1 to 100 nanometers and include metals, metal oxides, nonmetals, and carbon nanomaterials. They've been employed as bactericides, fungicides, and nano fertilizers due to their small size, extremely large surface area, and strong reactivity. NPs can be used as a biosensor for diagnosing plant diseases as well as delivery vehicles for genetic material and agrochemicals (Elmer and White, 2018). Nano sensors are a new technology that is being used in the agricultural industry to improve crop yield. Nanosensors are modified sensors that are used to detect disease, moisture, and nutrients in determining the most effective pesticide, water, and fertilizer dosages

(Rai and Ingle, 2012). The detection of pathogens that cause disease in crop plants is a possible use for nano sensors. Table (1) is used to identify pests and to assess the quality of the previous harvesting. Bioreceptor, transducer, and detector are the three primary components of a nano sensor. In the construction of sensors and diagnostic instruments, NPs with mechanical, electrical, photonic, and magnetic capabilities prove to be excellent. The nanotechnology-based sensor is used to assess insect damage caused by volatile organic chemicals generated by plants in cucumber, pepper, and tomato leaves. These sensors have been used to identify powdery mildew-infected tomato plants. A nano biosensor can detect soil conditions and provide data on the best chemical fertilizer dosages. One of the study areas has been the use of biosensors in the diagnosis of plant disease (Elmer and white, 2018). Sensors based on gold nanoparticles can be used to determine the retention of various pesticides in plants and food products. When comparing pymetrozene to 11 other pesticides, (Bai *et al.,*2010) found that the concentration of pymetrozene had a low detection limit and that the method had a high sensitivity for pymetrozene. AuNPs, which are produced by bacteria, are utilized to detect organophosphorus pesticide residues in fruits and vegetables (Malarkodi, 2017). The use of fungus-mediated AuNPs to remove pesticides and pathogens from the water was also reported by (Das *et al.,*2009). (Cui *et al.,* 2018) reported a chitosan-TiO_2-graphene nanocomposite-based nano sensor for organophosphate detection. Aflatoxin is identified in peanut samples using graphene-based biosensors that incorporate gold and graphene oxide nanocomposites (Li *et al.,* 2018) Nanomaterials are used to make biosensors because they have improved chemical stability, a higher surface area to volume ratio, and are biodegradable. Silver and Mercury ions have been found in serum and drinking water. Biosensors based on tungsten disulfide were used to analyze cell lysate, which has applications in diagnosis and environmental monitoring (Zuo *et al.,* 2016). A biosensor based on nanoparticles might be built for screening purposes, allowing for the detection of any chemical or microorganism (Kahveci *et al.,* 2016). The most important application in agriculture will be nano biosensors that can assess plant needs such as water and nutrient levels. Biosensors are also required to monitor the physiological processes of plant growth and soil conditions instantaneously. For micronutrients such as zinc and iron, a smart nano fertilizer delivery program has been created, in which the nutrient release mechanism is based on the identification and binding of a specific plant signal by a nano, biosensor in a polymer film that cots NPs, or salts of metals. (Duhan *et al.,* 2017; Kanjana 2017).

Agricultural waste management:

Due to particular restrictions in waste processing, agricultural waste can rot or degrade, potentially affecting crop productivity. By using metal nanoparticles as a catalyst, the effect of biofuel made from agricultural waste containing vegetable oils, sugarcane cotton stock, rice husk, coconut shell, and groundnut shell was optimized (Sarkar and Praveen, 2017; Bharti and Suresh, 2017) To reduce, bulk dosage, and enhance the hazardous agricultural waste into a harmless substance. Nanoparticles could be used as a catalyst (Ditta, 2012). For wastewater treatment, a variety of nanotechnology-based approaches have been used. In wastewater treatment, nano-based photocatalytic technologies are used for degradation, filtration, and purification of water and air. With the addition of semiconductors, it is also possible to eradicate pathogenic agents. When an NP is exposed to UV light, the chemical reaction is enhanced by the catalyst, which decreases the activation energy for the occurrence of the primary reaction. As a catalyst, nanoparticles incorporating metal oxides such as ZnO, TiO_2, and SnO_2 are utilized. (Feigl *et al.,* 2010).

Minimizing soil and groundwater pollution:

Polluted soil and groundwater can be treated by converting organic pollutants such as PCBs, dioxins, CCl4, and trichloroethene to less dangerous molecules using FeNPs as a catalyst (Joshi *et al.,* 2010). Biosynthesized FeNPs were used by (Wang *et al.,* 2014) to remediate eutrophic wastewater. Biosynthesized AgNPs as a catalyst for textile effluents were also degraded and biodegradable, according to (Nagar and Devra, 2019). According to (Gueye *et al.,* 2016), FeNPs used chromium (VI) from the soil through an adsorption mechanism. Furthermore, exopolysaccharide synthesis by Bacillus subtilis strain JCTI was used to biosynthesize ZnO NPs for barren soil application. Exopolysaccharide improvement was consistent, resulting in improved soil aggregation, moisture, and organic matter (Raliya *et al.,* 2014a). Biosynthesized AuNPs improved water purification by increasing membrane filter efficiency (Bharathi *et al.,* 2016). As a result, MNPs are effective for removing toxins from soil and water, as well as creating favorable circumstances for improving crop quality and production.

Table 1. Nanoparticle Applications in Agriculture Quality Improvement

Nanoparticles	Uses	References
Application in Seed Germination		
AgNPs	Corn, watermelon, and zucchini plants have significant effects on seed germination and seedling growth.	Almutairi & Alharbi (2015)
FeS2 NPs	Increase the productivity of spinach & different crops	Srivastava et al. (2014)
AgNPs	Induced seed germination & starch mobilization in Rice	Mahakham et al.(2017)
AgNPs,AuNPs,CuNPs	seed germination and biochemical profiling of *Artemisia absinthium*	Hussain et al. (2017)
FeNPs, CuNPs	Improved the yield of a wheat crop	Yasmeen et al. (2017)
Mg(OH)2Nps	Enhancement in germination rate of Z.Mays seeds	Shinde et al. (2020)
AuNPs	Induce cell division, seed & pollen germination	Thakur et al. (2018)
AgNPs	Enhancement in seed germination & growth	Manjunatha et al. (2016)
Ag2S,ZnS NPs	Enhancement in germination rate of soybean and wheat seeds	Afsheen et al. .(2020)
FeO NPs	Agent for enhancing germination of Pusa basmati rice seeds	Afzal et al. (2021)
Application in Crop Nutrition (As Nano fertilizer)		
FeO & ZnO NPs	Affect the growth of Vigna radiata seedlings	Dhokev et al. (2013)
ZnO NPs	Use as Nano fertilizer on a crop of Schoenoplectus Tabernaemontana	Zhang et al (2018)
ZnO,MnOx & FeOx Nps	As Nano fertilizer stimulate lettuce seedling by 12-54%	Liu et al. (2016)
AuNPs	As Nano fertilizer used on Arabidopsis thaliana	Kumar et al. (2013)
CeO2 NPs	As Nano fertilizer used on Arabidopsis thaliana	Ma et al. (2013)
ZnNPs	Applications as nano-fertilizers on pomegranate (Punica granatum cv. Ardestani) fruit yield & quality	Davarpanah et al. (2016)
ZnNPs, CuNPs	Applications as nano-fertilizers to obtain better quantity and quality in basil.	Abbasifar et al. (2020)
FeNPs, MnNPs	Applications as nano-fertilizers to affected lettuce seedling's growth.	de França Bettencourt et al. (2020)
Application in Pest & Disease control (As Nanocides)		
AlNPs (insecticide)	Significant mortality of pest S. oryzae L. & Rhyzopertha Dominica (F.) in cereals, beans & nuts	Stadler et al. (2010)
AgNPs (insecticide)	High efficacy & mortality (Sitophilusoryzae) in Rice Crop	Debnath et al. (2011)
CuO, ZnO & Mn_2O_3 NPs	Antimicrobial action towards plant pathogen(E.coli)	Kaweeteerwat et al. (2015)
AuNPs	Triggered trypsin inhibition of insects Aedes aegypti, beetles & mealy bugs	Patil et al. (2016)
AgNPs	Significant efficacy on insect Aedes albopictus & culex pipiens pollens	Fouad et al.(2018)
AgNPs (Nanofungicides)	Antifungal for pest Bipolaris sorokiniana on Wheat spot blotch disease	Mishra et al. (2014b)
AgNPs	Antifungal for pest Bipolaris sorokiniana on Wheat spot blotch disease	Mishra et al. (2014a)
AgNPs	Antifungal for wood-rotting pathogens in tree	Narayanan & Park (2014)
AgNPs	Antimicrobial activity for multiple pathogens	Mohamed et al. (2014)
AgNPs	Antibacterial against bacterial pathogen such as Staphylococcus, E Coli & Antifungal against fungal pathogen Candida albicans	Nayak et al. (2018)
CuNPs (as Nanobactericide)	Antibacterial against Xanthomonas campestris & Xanthomonas oryzae	Mondal & Mani (2012)
AgNPs	Antibacterial against pathogen Xanthomonas oxonopodies & Ralstonia Solana cearum	Aravinthan et al. (2015)
AgNPs	Antibacterial against pathogen Xanthomonas oxonopodies	Bhor et al. (2014)
CuNPs	Antifungal agent to protect chickpea plants from the pathogen, *Fusarium oxysporum* f. sp. *ciceri*	Sathiyabama et al. (2020)
SiO_2 NPs	An insecticide check against second and fifth instar larva of *Spodoptera litura* larvae	Sushila et al. (2020)
SeNPs	Use as a nano-fungicide for crop protection.	Joshi et al. (2021)
CuNPs	Antimicrobial activity against Agri-Food pathogens	Rajwade et al. (2022)
Application in improving Postharvest Quality of different Crops		
AgNPs	Applied at Gladiolus cut flower for reduced bacterial colonization & biofilm formation to enhance floret opening & prolonged vase life.	Li et al (2017)
AgNPs	Applied at Anthurium cut flower for prolonged shelf life, maintain water balance, reduced microbial count	Amen et al. (2017)
AgNPs (impregnated cellulosic packets)	Applied at Tomato & cabbage for enhancing the shelf life of vegetables	Singh & Sahareen (2017)

Table 1 Continued		
AgNPs	Make an active nanocomposite film to maintain the freshness of Strawberries.	Zhang et al. (2018)
ZnO2 NPs	Use in Fig Fruit(Ficus carica) to access the quality parameter & microbial formation	Lakshmi et al. (2018)
CuNPs	Use in Tomato vegetables as foliar to increases the fruit quality & content of biomolecules present in tomatoes	Lopez -Vargas(2018)
AgNPs	Applied as anti-microbial agents to control the postharvest biology of cut flowers	Naing et al. (2020)
AgNPs	Use in increasing shelf life of Morus alba L. at the post-harvest stage	Das and Mandal (2020)
Application in Weed Management (As Herbicide)		
MnO2 (core-shell protected with bilayer polymers)	Controlled release of the active ingredient after receiving rainfall	Chinnamuthu & Kokiladevi (2007)
MnCO3 (core nanoshell coated with water-soluble polymer)	Release of active ingredient on receipt of rainfall for rainfed cropping system	Kanimozhi & Chinnamuthu (2012)
AgNPs	Green synthesized NPs have a noticeable stress effect on P. minor as the reduction in GP% and growth as well as they may selectively inhibit unwanted weeds.	El-Darier et al. (2020)
Application in Monitoring Agro-Ecosystem (As Nanosensors)		
AuNPs	Pathogen detection in wheat crop disease Kamal bunt by Tillena indica (Fungus)	Singh et al. (2010)
AuNPs	Pathogen detection in citrus crop disease Tristeza by Tristeza(virus)	Shojaei et al (2016)
PtNPs	Determination of Adrenaline	Brondani et al. (2009)
PtNPs	Detection of pathogenic bacteria	Bu et al. (2019)
AgNPs	Detection of mercury ions in the water and soil samples.	Sowmyya et al. (2018)
AuNPs	Detection of multi-mycotoxin such as for fumonisin B_1, zearalenone, ochratoxin A, and aflatoxin B_1	Yuhao et al. (2020)

Food Applications:

Nanoparticles are used during the cultivation, processing, processing, and packaging of food, according to research from the European Nanotechnology Gateway (Xiaojia *et al.,* 2019). Because of their novel and unique qualities, NPs will continue to have a commercial impact on the food sector. Nanotechnology has a lot of potential in terms of color, flavor, and nutrition value alteration, as well as enhancing food storage life and monitoring food integrity via barcodes (Aigbogun *et al.,* 2017). Many aspects of customer products, such as food packaging, additives, and food preservation, have been incorporated with food nanotechnology. Food processing and storage have evolved as a result of the identification of this unique technology. Metal and metal oxide nanoparticles are added to food packaging materials to provide antibacterial and hygroscopic qualities for food preservation (Bajpai *et al.,* 2018; Xing *et al.,* 2019). Metal nanoparticles are used in edible coatings and films to keep fruits and vegetables fresh. AgNPs are the most commercially synthesized and used metal NP due to their antibacterial function, whereas AuNPs are being researched as a sensor or detector. TiO_2NPs are also used as a sanitizer, as well as a flavor enhancer and food additive. Other nanoparticles have shown great promise in essentially every element of the food industry. In the next sections, we'll go through some of the most recent developments.

Food processing:

Food processing incorporates the transformation of agricultural resources into a variety of processed foods used in the food business. Smart nutrition delivery, nano capsulation of nutraceuticals, bio separation of proteins, solubilization, sampling of pollutants, distribution, and color in food approach can all be enhanced. (Ravichandran, 2010). Various researchers are working on novel meals that will remain dormant in the body and offer nutrients until consumers activate them (Amin *et al.,* 2015). The addition of NPs to current food to validate greater nutritional absorption is a recent technique in food processing (Fig. 2).

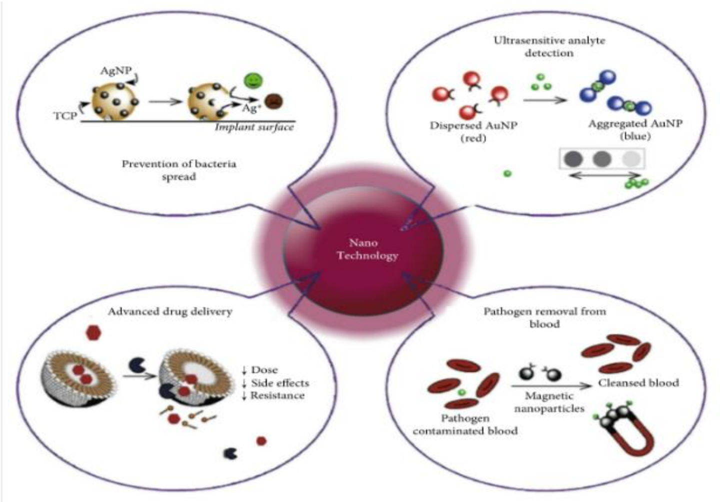

Fig. 2. Nanomaterial-Based Sensors for Food Quality. Data from (Hossain, A., Skalicky, M., Brestic, M., Mahari, S., Kerry, R. G., Maitra, S., ... and Islam, T. 2021). Application of Nanomaterials to Ensure Quality and Nutritional Safety of Food. *Journal of Nanomaterials*, *2021*.

Nanosensors:

Nanosensors are devices that detect contaminants, viruses, and bacteria in food systems to monitor the quality of food processing and food safety. Food pathogens may be attracted to NPs, and dangerous bacteria could be detected with sensors that use infrared light or magnetic materials. Nanosensors can get through those tiny c racks, and technology will speed up the detection process (Choudhury and Goswami, 2012). Nanosensors are essential for detecting pesticides in a variety of food products and ensuring food safety. Nanosensors are commonly employed to identify pesticides such as organophosphate in plants, fruits, and aquatics. The application of nano-sized materials with remarkable electrical and optical properties, such as metal nanoparticles (Ravichandran *et al.,* 2021) is anticipated to improve the sensitive transducer indications. Various technologies have been developed to detect pollutants, chemicals, and pathogens in food items, such as E. coli and salmonella (Chen *et al.,* 2008). Table (4.5).

Nanocapsule:

Nanocapsules can be introduced into food to deliver any nutrient, and the addition of NPs can help boost nutritional adoption (Jampilek *et al.,* 2019), extending the product's shelf life. Bioactive such as Q10 enzymes, vitamins, iron, and calcium have all been employed in nano delivery systems (He and Hwang, 2016). Through tailored delivery methods, nanoencapsulation can boost the bioavailability of bioactive substances following oral administration. This type of nanoencapsulation aids in the timely release of flavors as well as the prevention of taste decomposition during processing and storage (Yu *et al.,* 2018; Mahato *et al.,*2021).

Antimicrobial:

Bacterial identification is a widely contested topic when it comes to food production, processing, transportation, and storage. Antimicrobial activity has been documented for a variety of metals, metal oxides, and nanoparticles. Reactive oxygen species are formed as a result of their physicochemical qualities being absorbed. This causes oxidative stress and, as a result, cell damage (Wu *et al.,* 2014) In food packaging and coating, metal and metal oxide-based NPs are utilized. In the food business, silver NPs and their nanocomposite are utilized as antimicrobials (He and Hwang, 2016). Some polymers based on metal and metal oxide nanoparticles are developed to produce nanocomposites for use in the food industry. In food applications, nanocomposites of low-density polyethylene (LDPE) with metal (Ag) and metal oxide (CuO, TiO2, and ZnO) are utilized. In addition to chitosan, polystyrene, polyvinylpyrrolidone, and polyvinyl chloride are reported as nanocomposite films that connect to Cu and ZnO NPs to inhibit pathogen growth (Li *et al.,* 2009).

Antioxidants:

The production of reactive oxygen species by various metal/metal oxide nanoparticles leads to oxidative stress (Manke *et al.,* 2013). As a result, efforts have been made to produce nanoparticles that are less reactive and can act as antioxidant carriers. Browning of fresh-cut fruits is a major issue that can be addressed by using antioxidant treatments in conjunction with edible coatings. Browning of fresh-cut fruits colored pigments in the presence of air during storage and marketing is a major issue that can be addressed by using antioxidant treatments in conjunction with edible coatings (Garcia and Barrett, 2002). Fuji apples (as a fresh-cut product) had their shelf life extended utilizing nano-ZnO-coated active packaging (Li *et al.,* 2011) Table (4.5).

Enhancement of physical properties:

A wide spectrum of nanoscale color additives is created and utilized exclusively by approved purpose standards. (Hwang and He, 2016). Metal oxide TiO_2 NPs are recognized as a food color additive with a maximum concentration of 1%. v/v (Shi *et al.,* 2013). The use of color additive combinations made using TiO_2 (silicon dioxide) or aluminum oxide has also been approved, but only in amounts of less than 2%.

Flavors are one of the most important aspects of the food industry since they enable sensory identification of testing with scent to increase appetite and the eating experience. The usage of nanoencapsulation technology has been employed to improve flavor release and retention, as well as to provide dietary balance (Nakagawa, 2014). Foodstuffs could be fortified with iron by adding Fe and FeO NPs. They may affect excellent health by increasing hemoglobin and nutrition levels due to no change, such as fortified food, high stability, and bioavailability (Zanella *et al.,* 2017). Iran was reinforced as FeO NPs in the form of colorants in sausages (McClements and Xiao, 2017). (Razack *et al.,* 2020) claim that adding FeNPs to wheat biscuits increased iron concentration. FeNPs are made from the aqueous extract of Hibiscus -Rosa Sinensis petals. This study shows that FeO NPs can be used as food fortifiers (Table 1).

Packaging and food safety:

Food is perishable, and contamination can happen anytime in the food chain due to chemical, physical, or biological processes. As a result, food must be safeguarded at all times. Packaging of high quality, with nanomaterial control pH, temperature, moisture, and material freshness are all non-toxic, safe, and cost-effective (Yildirim *et al.,* 2018). Nanosensors are being developed for smart packaging to detect food rotting and, if necessary, release antimicrobials to improve shelf life. The use of NPs in packaging could be a new frontier in material science. It is widely considered that advances in nanotechnology, aided by increased worldwide investment, have driven the nano-enabled packaging market, all over the world in the past years (Nano-enabled packaging market, 2019; Fashola *et al.,* 2021). With recent advancements in nanotechnology, a variety of nanomaterials are now available for use in the food packaging system. In biopolymeric nano systems, such as cellulose, chitosan, and lignin demonstrates, literature, metal, and metal oxide nanoparticles are particularly efficient in terms of safety and environmental compatibility.

Biosensors:

In food safety and environmental monitoring, there is an ever-increasing demand for speedy, highly sensitive, and selective technologies. In this regard, nanotechnology-based biosensors have emerged as a highly effective and promising analytical tool. Food quality is defined as pathogen-free food that meets nutritional standards for customers. Everyday use of DDT, hexachlorocyclohexane, and pentachlorophenol result in food contamination and health issues (Abdou and Hend, 2018). As a result, the food industry requires practical and environmentally friendly technologies to check the freshness and contamination of GMO-free food. Biosensors have recently gotten a lot of interest as a way to make easier the analysis of industrial food products (Dragone *et al.,* 2017). Nanotechnology-based biosensors have been found to have excellent sensitivity and a very short detection time, which could play a key role in food quality and animal pollution reduction in the future. In less than five minutes, highly sensitive AuNPs-based nanosensors were constructed to detect V. parahaemolyticus in an oyster sample (Wu *et al.,* 2018). In 60 minutes, a magnetic NP and QD-based fluorescent Immunosensor detected E 0157:H7 (Xue *et al.,* 2018). The grapefruit's shelf life was extended thanks to AgNPs created by crosslinking with trisodium citrate. The antibacterial activity of Ag NPs packed with hydroxypropyl methylcellulose (HPMC) and xanthan films is good, with a low decay index (Kothari and Setia, 2017; Shelby *et al.,* 2017) utilized a magneto fluorescent nanosensor to detect E. coli O157: H7, a foodborne pathogen. Escherichia coli O157: H7 was detected in apple juice, milk, and ground beef using a piezoelectric biosensor based on an Au NP.

Food and the environment are both damaged by the agricultural industry's excessive use of pesticides. Biosensors can help in pesticide detection by allowing for faster and more precise detection. Chauhan et al. (2019) developed acetylcholinesterase (AChE) immobilized AChE/Fe3O4-MWCNT/Au electrodes, ZnS, and poly-modified Au electrodes, and Fe3O4 NPs/multiwall Carbon Nanotube based sensor for organophosphorus pesticide detection at the nano level. Similarly, due to its sensitivity and accuracy for pest and insecticide detection in agriculture, AuNPs conjugated SPR Immuno sensors have been reported to improve atrazine detection signals in maize crops (Liu *et al.,* 2015b). (Table 5). The use of receptors was used to improve the sensitivity and detection limit of the Xanthine biosensors. Rhodamine B capped thioglycolic acid-functionalized AuNPs based on fluorescent Xanthine biosensor study report. The fluorescence signals in the coffee sample were studied because it is utilized to degrade Xanthine in uric acid (Menon and Kumar, 2017).

Furthermore, a biosensor based on AuNPs has been designed to detect pesticides such as methyl paraoxon, carbofuran, and phoxim. AuNPs catalyze the oxidation of Thiocholine, which can subsequently be sensed to identify the presence of insecticide, by promoting quick electron transfer reactions at a lower potential (Yin *et al.,* 2009). AuNPs with tyrosine caps have enzyme-like activity and can detect kanamycin utilizing particular aptamers attached to the NPs (Sharma *et al.,* 2014). This is a useful technique for detecting kanamycin residue in food. Functionalized AuNPs can be used as food packaging to prevent microbial contamination. They can also be made into composites with polymer to act as a buffer that prevents moisture exchange and hence food fouling. Due to the ultrasensitive features of NPs, other applications in food packaging such as pesticide detection (Saho *et al.,* 2018) pathogen detection (Sun *et al.,* 2018), and toxin detection (Sun *et al.,* 2018) are being developed. ZnO quantum dots (QD) can be used to detect pesticides including Aldrin tetradifon, atrazine, and glyphosate, according to Saho et al. Pesticides with a strong living group (e.g., Cl) interact with QD with high binding affinity, and ZnO QD could photo catalyze pesticides during the interaction, according to the findings.“Smart packing” nano has become a popular trend to use NPs based sensors for monitoring the quality of food.

Time-temperature, integrated, and gas detector nanoparticle-based sensors are employed in a variety of food sectors (Pradhan *et al.,* 2015). Visual color changes in metal/metal oxide (Ag/Au/Fe_3O_4/ZnS) NPs sols in the presence of analytes (Ang *et al.,* 2016) AuNPs based sensors are used to identify pathogen V. *Paraha emolyticus* on oyster samples (Ang *et al.,* 2016). (Wu *et al.,* 2018). Food safety will be monitored, recorded, and translated using Time-Temperature Indicators (TTI Nanosensors). By using time travel, a system based on AuNPs for chilled food has been developed. (Robinson and Morrison, 2010). Gas sensors are also used for the identification of numerous microorganisms. Metal oxide gas nanosensors are mostly utilized due to their high sensitivity and stability (Setkus, 2002) (Table 2).

Nanofillers:
Metal and metal oxide nanofillers, such as Au, Ag, Fe, TiO2, ZnO2, CuO, and MgO, have been utilized in food packaging as antibacterial agents (Kaur and Kalia, 2016; Carbone *et al.,* 2016). Antimicrobial qualities are determined by the amount of highly reactive oxygen species (ROC) produced, which are toxic to pathogenic microbes. The antibacterial potential of dual or multiple metal/metal oxide nanoparticles (such as Ag, TiO2 against E.coli, and Bacillus Cereus Sp.) has been observed. When a packaging material with modified qualities is not feasible, a coating on the surface of the fruits can be used to extend the quality of the past harvest. (According to Sogvar *et al.,* 2016), the nano ZnO coating on strawberries can control the growth of aerobic bacteria, yeast, and mould during storage. Orange juice was poured into nanocomposite film containers and stored at 40°C, with the microbiological stability of the juice being assessed after various periods of storage. The rate of microbial growth was dramatically lowered by utilizing nanocomposite packing material, according to the findings. (Peter *et al.,* 2015) created an Ag/ TiO_2- SiO_2 coated food-packaging film that they used to inactivate Botrytis Cinerea during fresh lettuce storage. According to reports, the lettuce's shelf life was prolonged to five days. (Peter *et al.,* 2016) also examined the microbiological and chemical aspects of white bread that have been treated with Ag/ TiO2- SiO2, Ag/ N/TiO2, or Ag/ TiO2 NPs during storage in paper containers. TiO_2 Nanoparticles are utilized in food packaging and storage as a food additive, lightening agent, and antibacterial agent. Yemmireddy and Hung, (2015) used TiO2 and binders to make diverse suspensions, and they tested bacterial activity against E. coli 0157: H7 at various UV light intensities. ZnO NPs are utilized in food packaging as an antibacterial agent (Sirelkhatim *et al.,* 2015). The ZnO NPs coated starch Polythene film has a lot of potential as a food packaging material to keep food safe (Table 1).

Oxygen Scavengers:
By oxidizing pigments, vitamins, microbial development, color change, and nutritional losses, the presence of oxygen in food packages can significantly reduce the shelf life of food (Cichello, 2015). The iron-based oxygen scavenger can scavenge oxygen from foods and beverages that contain intermediates or have a low moisture content (Suman and Suk, 2018).

Detection of heavy metals in food:
Heavy metal components in food that are beyond certain concentration thresholds can be harmful to human health. Colorimetric sensors that use AuNPs to detect Hg+2 have been produced. Thymine has a strong affinity for Hg^{+2}, which Chen and colleagues used to develop a microfluidic platform for the detection of Hg^{+2} by coordinating T- Hg^{+2} -T. The agglomeration of AuNPs caused the color shift (Chen *et al.,* 2014; Yin *et al.,* 2011) developed a surface-enhanced Raman scattering sensor to detect Cd^{+2} due to self-aggregation of AuNPs due to interplasmonic particle interaction in the presence of Cd^{+2}. The reduction of Pb^{+2} caused by synergistic catalysis of Pt @ Pd and MnTMPYP to H_2O_2 resulted in a signal increase (Zhao *et al.,*2017). To detect Hg^{+2}ions, tryptophan-capped AuNPs were employed as surface-enhanced Raman spectroscopic probes (Senapati *et al.,* 2011). This type of technology is useful for identifying heavy metal contamination in foods.

Table 2. Applications of Metal/Metal oxide nanoparticles in the Food sector

Nanoparticles	**Uses**	**References**
Application in Food Processing		
TiO2	Colour Additive	Code of Federal Regulations (2018)
ZnO, FeO & Al2O3	Additive or polymer production aid	The European Commission (2011)
Ag-Si	Preservatives	U.S. FDA. Inventory of effective food contact substance
CuO,FeO,ZnO	Nutritional dietary supplement	U.S. FDA. Food additive status list. US FDA/CFSAN Office of Food Additive Safety (2018)
FeNPs & Nanocomposite	As Nanocapsule used in nano delivery system	He & Hawang (2016)
AgNPs & Nanocomposite	Antimicrobial agent	He & Hawang (2016)
TiO_2	Nanoadditive	Shri et al. (2013)
Fe,FeO	Naneutricals	Zonella et al. (2017)

Table 2 Continued		
FeNPs	Food Forticants	Razak et al. (2020)
AuNPs	As colorimetric sensors used in the detection of chemical contaminants in food samples	Chen et al. (2018)
AuNPs	As Biosensors used in melamine detection in food safety testing	Zhou et al (2020)
AgNPs	Nanosensor	Ravichandran et al. (2021)
Application in Food packaging		
ZnO QDs	Pesticides detection	Saho et al. (2018)
Magnetic nanosensors	Pathogens detection	Sun et al. (2018)
Fluorescent nanosensors	Pathogen detection	Banerjee et al. (2016)
Phosphorescent QDs	Toxins detection	Zhang et al. (2017)
AuNPs Optasensor	Pathogen detection	Wu et al. (2018)
Magnetic NPs & QD based Fluorescent Immunosensor	Pathogen detection	Xie et al. (2018)
Ag-Pb recognition based SPR biosensor on AuNPs	Pathogen detection	Liu et al (2015 b)
Rhodamine B capped thioglycolic acid-functionalized AuNPs	Pathogen detection	Menon & Kumar(2017)
TiO2 NPs	Photocatalytic, antibacterial agent & oxygen scavenger	Hoseinnejad et al. (2018)
ZnO NPs	Antibacterial & U.V. protecting agent	Coralia et al. (2018)
AgNPs	Antibacterial agent & Nanosensor	Ryspayeva et al. (2018), Tripathi et al. (2018)
AuNPs	Food borne-pathogens detection	Hua et al. (2021)
Ag/TiO_2 Nanocomposite	Antibacterial Agent	Abutalib et al. (2021)

Conclusion and Future Perspectives:

The various advantages and applications of metal nanoparticles listed above indicate that nanotechnology has the potential to transform the Agri-food sector, while also assisting in the resolution of significant issues such as food scarcity, crop productivity, and sustainability. The encapsulation properties of these MNPs were investigated using a variety of plant-derived bioactive compounds, fertilizers, and pesticides that might be encapsulated into the nanoparticles for use in food fortification, edible packaging, and agricultural activities. Furthermore, demonstrating the various ways in which biogenic NPs can be used to replace hazardous nanoparticles in their current roles in food and agriculture serves as a safer way to gain the benefits of nanotechnology. Furthermore, the biodegradable and safe nature of such materials makes them suitable for use in food and agriculture. As a result, using these materials for Agri-food uses would be a sustainable method. The successful integration of these materials into various systems would allow us to take advantage of their inherent unique advantages to a greater extent.

Regulation and legislation are also important in regulating nanoparticle manufacturing, processing, application, and disposal. Public understanding and adoption of revolutionary nano-enabled food and agriculture products still need to be improved. We conclude that nanotechnology offers a plethora of potential in the food and agriculture industries by giving an innovative and sustainable alternative.

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