NIGERIAN AGRICULTURAL JOURNAL
ISSN: 0300-368X
Volume 55, Number 3, December 2024, Page 92-110
Available online at: http://www.ajol.info/index.php/naj
https://www.naj.asn.org.ng

Unveiling the Potential of Silver Nanoparticles: A Comprehensive Review of Their Application in Agriculture and Food Industries

Onyegbula, A.F., *Oyeyipo, S.O., Ahmed, T., Adediran, B.I. and Adegbola, R.Q.
Nigerian Stored Products Research Institute, Ilorin
*Corresponding author's email: oyeyipostephen@gmail.com

Abstract
The field of nanotechnology has brought about a remarkable transformation in the food industry, introducing new technological advancements that have the potential to revolutionize the Agrifood sector. Nanoparticles, in particular, have become a viable resource for enhancing global agricultural production, enhancing nutritional value, and ensuring food safety and quality. One of the many varieties of nanoparticles is Silver nanoparticles (AgNPs),, which are widely utilized for their potent anti-bacterial and bactericidal properties and their wide range of antibacterial effects. The nanoparticles are typically produced by utilising three distinct methods, including chemical, physical, and green synthesis (biological techniques). The green synthesis strategy is the most commonly used, since it is affordable and environmentally beneficial. AgNPs have a wide range of uses in the food and agricultural industries, including Nanofertilizers, Plant Growth Aid, Pesticide Remediation, Plant Disease Management, Crop Protection, Food Processing, Food Packaging, Safety Enhancement, Quality Monitoring of food, Nano-sized Additives, Nutraceuticals, etc. Nanoparticles continue to drive innovation in the food and agricultural industry, from innovative packaging solutions to advanced sensing technologies and novel processing techniques. Nanotechnology has become an indispensable tool for addressing existing difficulties associated with packaging materials, positively impacting the quality, safety, and security of foods, and being advantageous to producers and consumers.
Keywords: Antimicrobial, Food industry, Nano fertilizers, Nutraceuticals, Pesticide remediation

Introduction

Research in the realm of nanotechnology presents a wealth of opportunities in various sectors of science and technology (Sharma *et al.,* 2023). Using substances such as atoms, molecules, or macromolecules that range in dimensions from 1 to 100 nm, innovative nanotechnology has transformed the food industry. This involves the development and utilization of materials possessing distinct characteristics (Shafiq *et al*., 2020; Thiruvengadam *et al*., 2018; Tripathi *et al.*, 2017). In addition to having the ability to improve food safety, quality, and nutritional content,

Nanotechnology has also emerged as a technical innovation to enhance and alter the agrifood business (King *et al*., 2018). Its applications have emanated from the growing need for the application of nanoparticles in food science and microbiology across a wide range of domains, especially in food safety (Tripathi *et al.,* 2017). Its importance in producing food packaging with improved mechanical, thermal, and electrical qualities and safety also made nanotechnology a gift for the food chain (Sharma *et al*., 2023; Shafiq *et al.,* 2020). Nanoparticles (NP) are increasingly being used in the food industry for various purposes such as food processing, packaging, and storage. In the field relating to the processing of food, Momin *et al*. (2013) reported that nanocapsules have been used as functional foods, additives, nutritional supplements, and nano-sized components. Cushen *et al*. (2012) stated that protective barriers, flavour and taste masking, controlled release, and improved dispersability for water-insoluble food components and additives have all been achieved by the nanoencapsulation process.

The agricultural sector is one of the major sectors providing food for humans, and it is faced with challenges such as climatic extremes, water scarcity, limited land mass, as well as inadequate air and water quality. To address these issues, the agriculture sector is exploring frontier technologies like utilising nanotechnology to create innovative methods to enhance agricultural yield, protect the environment, and boost farming efficiency (Sonali *et al*., 2021). There are many different kinds of nanoparticles, such as metal, ceramic, and carbon-based NPs (Chaudhry*,* 2009). Metal nanoparticles (NPs) include silver nanoparticles (AgNPs), which are essentially nanoparticles of chemicals linked to silver. Due to their distinct physical and chemical characteristics, silver nanoparticles (AgNPs) are being employed more and more in a variety of industries, including food, medicine, consumer goods, and healthcare. Biological qualities, strong electrical conductivity, and optical, electrical, and thermal characteristics are a few examples of fields where silver nanoparticles are being applied (Gurunathan *et al*., 2015; Li *et al*., 2010; Mukherjee *et al*., 2001).

For biosystems, nano-silver is the most researched and used nanoparticle. It possesses a wide range of antimicrobial activity and has been shown to have potent bactericidal and inhibitory effects. Silver nanoparticles, which have a high surface area and a high fraction of surface atoms, have a high antimicrobial effect as compared to bulk silver. Thus, this review discusses the potential of silver nanoparticles and their uses in the food and agriculture industries.

Synthesis of Silver Nanoparticles (AgNPs)

Silver nanoparticles can be synthesized using three different approaches, such as physical, chemical, and green synthesis.

Physical Methods

This method is employed for easy and safe preparation of pure metal colloids in such a way that the solutions do not contain any dangerous chemical additives (Kanwar *et al*., 2021). Physical methods of synthesizing AgNPs involve Laser ablation, irradiation, evaporation, condensation, and lithography processes (Güzel *et al.,* 2018). The sizes and homogeneity of nanoparticles produced using this method are the best compared to those produced by chemical processes (Pugazhenthiran *et al.,* 2009). This process uses four different energy sources:

- light energy (from laser ablation),
- Electrical energy (from electrical arc-discharge method),
- Thermal energy (from the physical vapour deposition method), and
- Mechanical energy (from the ball milling method).

Although the physical synthesis of AgNPs uses a furnace with an atmospheric pressure tube to produce NPs through evaporation and condensation (Banerjee *et al.,* 2022), it proves to offer several unique advantages. This includes excellent purity, a quick synthesis reaction rate, an absence of contamination from solvents, and the procedure is free from dangerous compounds such as reducing agents and stabilizers (Nguyen *et al.,* 2023). However, some of the challenges with this methodology include the fact that it requires a lot of energy to operate in running the furnace and takes up a considerable amount of space during the operational procedures (Pugazhenthiran *et al.,* 2009). Aside from the fact that it takes a lot of time, this method also has a poor potential yield and significant energy consumption (Shameli *et al.,* 2010). Also, the increasing environmental temperature makes it a very tough job, especially in achieving thermal stability (Kanwar *et al.,* 2021).

Chemical Methods

The most used technique for producing AgNPs is chemical synthesis, and it requires three reactant components that are: a stabilizing chemical, a silver salt precursor, and a reducing agent (Nguyen *et al.,* 2023). The reducing agent (sodium borohydride, sodium citrate, ascorbic acid, various alcohol types, and certain hydrazine compounds, for example), also known as the metal precursor, often serves as the capping agent (Kanwar *et al.,* 2021). Elemental silver is produced by reducing the silver ion (Ag+) from precursor silver salt nanoparticles (AgNPs) using the movement of the electron transfer. Stabilizing agents are surfactants that contain functionalities that serve as a protectant for the coat of AgNPs, thereby protecting the NP surface (Iravani *et al.,* 2014). This further helps in preventing additional AgNPs from adhering to or absorbing on the NP surfaces, which could cause agglomeration (Kim *et al.,* 2004).

Chemical synthesis of AgNPs involves nucleation and growth when the concentration of the silver element in a solution exceeds the critical level of supersaturation. This process produces high yields with no aggregation, despite high production costs and hazardous consequences (Mallick *et al.,* 2004). However, excessive stabilizer use can reduce AgNP production and leave chemical residues on the surface, making it hazardous for drug production and antimicrobial applications (Vishwanath *et al.,* 2021). Large-scale chemical synthesis is not sustainable (Nguyen *et al.,* 2023).

Green or Biological Synthesis

Traditional techniques often involve toxic chemicals, high energy consumption, and hazardous by-products. In contrast, green synthesis leverages biological entities and environmentally friendly solvents, aiming for sustainability and safety (Rana *et al*. 2008). Green chemistry is the foundation of the green synthesis approach, which is an environmentally friendly synthesis method. It utilizes natural resources, such as plants, microorganisms, and biopolymers, to generate nanoparticles (Mukherjee *et al.,* 2001; Nakamura *et al*., 2019). For the synthesis of nanoparticles, a variety of natural sources can be employed, such as bacteria, fungi, yeast, plants, and their products (Pugazhenthiran *et al.,* 2009). The utilisation of plant extracts is one of the greener ways to synthesise Ag NPs that is now available. Compared to fungi- and/or bacteria-mediated synthesis, this method is considerably simpler and easier to do on a large scale.\by enzymatic reactions of the enzyme Nicotinamide adenine dinucleotide-dependent reductase; however, the enzymatic reduction rate is often slow (Ali *et al.,* 2011; Ramesh *et al.,* 2012). pH and reaction temperature are two parameters that have been studied as potential accelerators of Ag NP production. Environments that are neutral or slightly alkaline are preferred since highly acidic environments cause the denaturation of proteins and polysaccharides. The amount of reactant consumed within the reaction system greatly increases at high temperatures, yielding nanoparticles. Small-sized particle production requires an appropriate synthesis technique because the diameter of the AgNPs is known to influence the microbiological while bactericidal activity is enhanced with lower particle sizes (Nakamura *et al*., 2019).

Silver Nanoparticle Characterization (AgNPs)

The purpose of the characterization study of silver nanoparticles is to examine their size, shape, and other distinguishing characteristics, in addition to verifying that they exist. Silver nanoparticles can be characterized using the method below;

UV-Vis Spectroscopy:

Reduced silver ions as silver nanoparticles are identified and verified in the algal culture using UV-Vis spectroscopy. The 200 nm to 700 nm wavelength range is utilized to measure absorbance. UV-Vis spectroscopy encompasses both the visible and UV ranges (Poole, 2000).

Scanning Electron Microscopy (SEM):

This device works similarly to an "optical microscope" in that it enlarges images by using a glass lens and a light source. By scanning a sample laterally, electron microscopy provides information on its topographical characteristics and atomic composition. Three analysis methods are programmed into surface sensing imaging (SEM): "X-ray energy dispersive spectroscopy, secondary electron (SE) mode, and backscattered electron (BSE) mode (Zhou and Tang, 2018).

Transmission Electron Microscopy (TEM):
TEM is a frequent tool for creating contrast images with certain good crystal surfaces (Filipponi, 2010). It can be used to determine the size, shape, and aggregation state of metal nanoparticles. The particle distribution and size profile of scattered particles are assessed using TEM, which uses an electron beam to take a snapshot of the image kept for identification (Tiede *et al.,* 2008).

Fourier Transform Infrared Spectroscopy (FT-IR): The FTIR spectrometer is used to study the chemical architecture of silver nanoparticles. The powder that results from drying the nanoparticle solution at 75°C is characterized within the range of 4000 to 500cm-1. FTIR spectroscopy is used to record infrared absorption or emission spectra. A light with a frequency range of 5000400 cm (Chekli *et al.,* 2016).

AFM (Atomic Force Microscopy) is a technique used to examine whether atoms are present on the surface of nanoparticles or not. AFM allows for a complete analysis of the surface chemistry of nanoparticles (Anith *et al.,* 2022).

X-Ray Diffractometry (XRD)*:* Using graphical data from XRD, researchers may examine the size and composition of silver nanoparticles. X-ray crystallography (XRD) is based on Bragg's law (Khorrami *et al.,* 2018; Anith *et al.,* 2022). Monochromatic X-rays, known as "diffracted X-rays," significantly interfere with the crystal sample. As an alternative to evaluating the purity of the material, XRD can be used to assess the rates of crystallization, identify minuscule spark elements in nanoparticles and nanoclays, and carry out "unit cell size analysis." Materials must be ground and homogenized to perform an accurate XRD examination (Fathima *et al*., 2018).

Silver Nanoparticles' (AgNPs') Mode of Action

There are two mechanisms of action utilized by AgNPs to cause death to microorganisms, and these include;

Mechanisms of Antibacterial Action via Direct Contact with Microorganisms

When compared to bulk silver, AgNPs have better physicochemical and biological qualities. They can infiltrate bacterial cell walls, causing membrane damage and potentially causing leakage of cellular contents and bacterial death. Gram-negative bacteria are more susceptible to AgNPs' antibacterial action. This is explained by the differential in the thickness of the cell walls between bacteria that are Gram-positive (30 nm) and those that are Gram-negative (3–4 nm) (Roy & Chatterjee, 2021). The positive charge of nanoparticles is attracted to the negatively charged cellular membrane of bacteria, enhancing their antibacterial effects (Abbaszadegan *et al*., 2015; Mandal *et al*., 2016). The surface charge of AgNPs can be altered to achieve a stronger attractive force. Smaller nanoparticles have a larger surface area, reaching the cytoplasm more often than larger ones (Khalandi *et al*., 2017). This leads to bacterial malfunction and cell death, especially through their interactions with biomolecules and cellular structures of such bacteria (You *et al*., 2012). Furthermore, AgNPs can generate large amounts of free radicals and reactive oxygen species (ROS), which give them antibacterial capabilities, which can be eliminated by antioxidant systems (Zhao *et al*., 2021; Gomaa *et al*., 2021). They inhibit cell growth and respiration by inactivating respiratory chain dehydrogenases and down-regulating antioxidant enzyme expression (Quinteros *et al*., 2016). Apoptosis-like reactions, lipid peroxidation, GSH depletion, and DNA damage are all caused by increased ROS (Lee *et al*., 2018; Korshed *et al*., 2016).

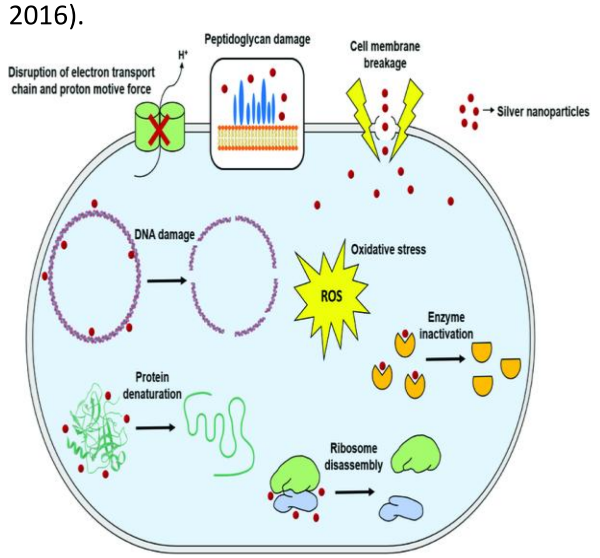

Figure 1: Mechanisms of AgNPs action against microbes
Source: Roy et al. (2019)

The Mechanisms of Antibacterial Action Assisted by the Discharge of Silver Ions

AgNPs exhibit antibacterial activity due to their silver ions (Ag^+) release, which is influenced by their surface area (Lombardo *et al*., 2016; Kim *et al.,* 2016). Silver ion (Ag+) concentration is discovered to be highest in AgNPs with the largest surface area, while weak antibacterial capabilities arise from the lowest concentration (Zawadzka et *al*., 2014). The mode of function of Ag+ in proteins and enzymes is by interacting with sulfhydryl groups. Membrane penetrability is crucial in respiratory processes, as proteins like silver ion Ag^+, are involved in ion transport and transmembrane ATP synthesis (Klueh *et al.* 2000). Also, Ag+ can inhibit respiratory chain enzymes, uncouple electron transport, and block protons and phosphate from passing through membranes, which stops cell division and reproduction (Monteiro *et al*., 2018). Silver nanoparticles (AgNPs) coated with ligands have been found to have an antibacterial mechanism by increasing cellular oxidative stress in microbes (Long *et al*., 2019). This oxidative stress, induced by Ag^+, interacts with respiratory chain proteins, interrupting intracellular O_2 reduction and causing ROS production (Gon *et al*., 2006). Bacteria utilize the thioredoxin system, a main disulfide reductase pathway, to combat oxidative stress. A synergistic impact between AgNPs and Ag+ represents the antibacterial mechanism (Siritongsuk *et al*., 2016).

AgNPs Application in Agriculture

The most cutting-edge area of agriculture is nanotechnology, which is attracting much attention from scientists worldwide. In the pharmaceutical and medical industries, AgNP applications have also attracted a lot of attention and promotion (Khan *et al.,* 2023). The application of AgNPs in agriculture, however, is a relatively recent field of study. Conversely, AgNPs' antioxidant, antibacterial, antifungal, anti-viral, and anti-inflammatory properties have been explored in recent revealing their role in enhancing seed germination and improving crops. This indicates that the most researched and used nanoparticle for biological systems is nanosilver.

Figure 2: Nanoparticles in Agric-Food
Source: Duncan (2011)

There are diverse applications of silver nanoparticles in agriculture; though they are mostly theoretical, some of such applications have a favorable impact on the plant. Such impacts are as follows:

Released Nanofertilizers under Control

The application of AgNPs in synthesizing nanocapsules for the controlled release of agrochemicals has attracted significant attention as a result of their exceptional stability, biodegradability together with capability to delay or extend the release of active compounds. This approach holds great potential for optimizing the administration of fertilizers, insecticides, and other agrochemicals in agricultural practices (Chowdappa and Gowda 2013). According to research, utilizing AgNPs as a nanofertilizer is considered the most effective approach for regulating the delivery of nutrients to plants. Nanoparticles containing agrochemicals are precisely designed to possess key attributes, including ideal concentration, gradual and controlled release, heightened efficacy at the intended location, and minimal harmful effects (Tsuji, 2001). Through dissolving, biodegradation, diffusion, at a certain pH, and osmotic pressure, it aids in the regulated, gradual release of agrochemicals to the specific host (Singh *et al*., 2020). Nano-tagged agrochemicals lessen the chance of some chemical contamination that occurs in the environment and reduce damage to plant tissues that are not intended for them (González-Melendi *et al.*, 2008; Rai *et al*., 2012).

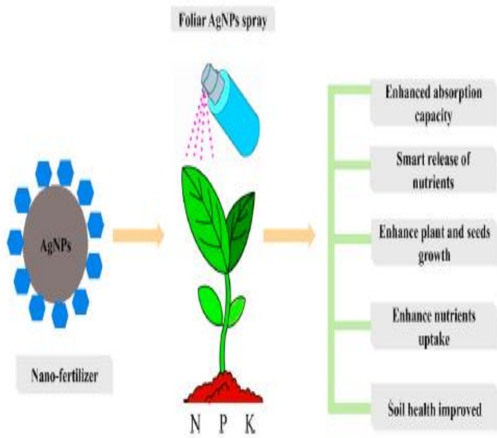

Figure 3. The foliar spray of AgNPs
Source: Sajad et al. (2023)

Positive Effect on Plant Growth

Research has shown that specific plant species can experience advantages from utilizing nanoparticles, leading to a high rate of crop yield as well as enhanced growth and development of seed (Servin *et al*., 2015; Arruda *et al*., 2015). Silver nanoparticles (AgNPs) have been reported as a potential method of promoting plant and seed development, hence boosting crop productivity. The effects (both positive and negative) of silver nanoparticles on the growth and development of plants depend on the concentration of the AgNPs. The effects of biogenic AgNPs on the growth metabolism of Bacopa *monnieri* that were cultivated were examined and their findings show that AgNPs had a noticeable impact on the growth of the seed, promoted protein and carbohydrate production while there was a reduction in the phenolic content, catalase, and peroxidase activities (Krishnaraj *et al*. 2012). Biologically produced AgNPs were also reported to improve *Boswellia ovalifoliolata* tree seedling germination and growth (Savithramma *et al*., 2012). In Brassica juncea, common bean, and corn plants, AgNPs were observed to enhance the morphological (shoot and root length, leaf area) and biochemical (chlorophyll, carbohydrate and protein contents, antioxidant enzymes) properties (Salama, 2012; Sharma et al., 2012). However, depending on the type of plant, Gruyer *et al*. (2013) discovered that AgNPs' impact on root elongation differs; barley had an increase in root length, but lettuce had a decrease in it. Studies have demonstrated that the effects of silver nanoparticles on plants vary, particularly due to variables like form, zeta potential, size, concentration, chemical constituents, and stability (Mirzajani *et al.*, 2013; Tripathi *et al*., 2015, 2017; Costa and Sharma, 2016). According to Tripathi *et al* (2017), research reports have also pointed out that nanoparticles can negatively impact plants, resulting in reduced growth, productivity, and pigmentation. AgNPs of a size range 200–800 nm are reported to aid general plant growth (Jasim *et al*., 2016); while those of a size range 35–40 nm are known to positively influence the growth of various plant species' roots and shoots (Pallavi *et al*., 2016). This may be because larger nanoparticles are less able to penetrate the plant (Mirzajani *et al*., 2013). Furthermore, silver nanoparticle size (<30 nm) was found to generally inhibit the growth of both shoot and root in various plants when applied in high concentrations (Dimkpa *et al*., 2013; Vinković *et al*., 2017). Al-Huqail *et al*. (2018) found that treating Lupinus term seedlings with 100 ppm bio-AgNPs improved their growth, while exposure to higher concentrations (300 and 500 ppm) significantly decreased their growth characteristics and indices.

Pesticide Remediation

The agriculture industry faces significant risks from pests, which leads to a great reduction in crop productivity and crop quality, additionally harming the ecosystem by using chemical pesticides on the plants and soil. An innovative method for managing and controlling pests that are important to agriculture is the use of nanopesticides. The primary significance of nanocides, or pesticides based on nanotechnology, is in their environmentally friendly nature and their little impact on insects that are not intended targets. It also shields the plants from pests and gives them extra nutrition, thereby bringing about a reduction in the use of chemical fertilizers regularly in conventional farming. Additionally, it eliminates dangerous germs from soil as well as hydroponic systems. Applying foliar spray of AgNPs helps prevent rot, mould, fungus, and many other microbially related plant diseases (Babu *et al*., 2013). It has been reported that applying aqueous silver solution to plants has good preventive effects on pathogenic bacteria that cause powdery mildew or downy mildew in plants (Yokesh *et al.,* 2014). AgNPs can be utilized to effectively break down pesticides and have been extensively studied in modern technological research. AgNPs have been successfully applied to remove pesticides "chlorpyrifos" and "malathion" from water, as reported by Manimegalai *et al* (2011). It has been demonstrated that these nanoparticles actively bind pesticides to their inert surfaces, offering a viable strategy for the total elimination of pesticides from water sources. Biologically produced pesticides exhibited anti-microbial activity, demonstrating their ability to combat bacteria and fungi that cause a range of agricultural losses (Amin, 2020). *Solanum lycopersicum is* used for the synthesis of silver nanoparticles of size 50–100 nm. These were applied to *M. rosae* at concentrations of 200, 300, 400, and 500 ppm, and distilled water was used as a control. The mortality rate of AgNPs from this showed optimum efficacy at 500 ppm concentration, that is, the mortality rate was associated with higher concentrations (Bhattacharyya *et al.,* 2016). Three different kinds of silver nanoparticles were utilized in different investigations to examine the larvicidal potential of *Tenebrio molitor*, a larval stage at sixteen. More than 70% of insecticidal effects on larval viability were observed with AgNPs and silicon dioxide microparticles (Rankic et al., 2021).

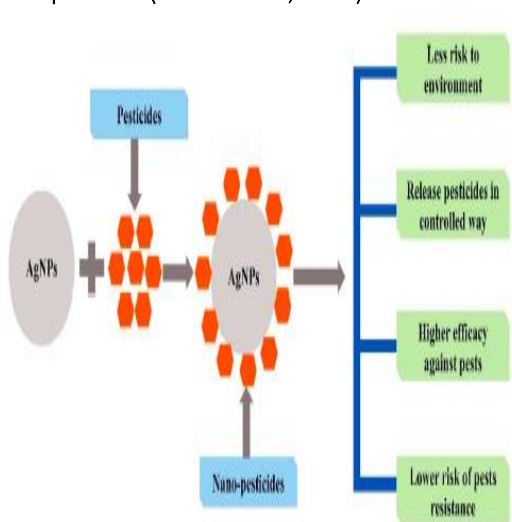

Fig. 5. AgNPs-based Nano fertilizers
Source: Sajad et al. (2023)

Plant Disease Management and Crop Protection

Maintaining the health of plants is essential for the well-being of both animals and humans, yet this topic is often overlooked in health-related literature. Plants play a crucial role in providing over 80% of human food and functioning as the main supply of nourishment for cattle. Plant diseases and pest infestations, however, may be a danger to the availability of plants and the safety of food for people and animals. Global crop losses amount to 30% and result in significant financial losses in food production (Rizzo *et al*., 2021). According to Gru'ere (2012), nanotechnology offers a safe and highly effective approach to improving precision farming and producing healthier food. Being a mechanism that is being used as nano-antiviral, nano-antibacterial, and nano-antifungal agents, nanotechnology can protect plants from various threats, including targeted microbes in soil, hydroponic systems, and plants. The control of plant diseases in fruits and food crops is an area of critical research with significant economic implications. Researchers have found that colloidal silver nanoparticles (AgNPs) are highly effective bactericides and fungicides because of their strong adherence to the cell surfaces of bacteria and fungi. By applying AgNPs on Graphene oxide-produced silver nanoparticles using DNA, researchers have achieved promising results in disease control. Additionally, they evaluated these nanoparticles' antibacterial efficacy against *Xanthomonas perforans*, the bacterium that causes tomato bacterial spots. Plant extracts' antimicrobial properties are attributed to glycosides, tannins, and saponins, which are all examples of secondary metabolites (Polash *et al*., 2017). Bacterial diseases significantly contribute to crop yield loss on a global scale. Silver nanoparticles (AgNPs) have demonstrated effectiveness towards bacteria-causing pathogens in plants. Studies have shown that AgNPs exhibit strong antimicrobial activity compared to traditional antibiotics, especially against *Erwinia carnivora* and *E. coli* (Alloway, 2008). Additionally, promising results have been obtained from research indicating the antifungal effects of AgNPs against pathogenic fungi, including *Fusarium oxysporum*, *Alternaria* *alternata*, and *Aspergillus flavus*. Colloidal nanosilver (with an average diameter of 1.5 nm) has demonstrated efficacy in preventing rose powdery mildew, which is caused by *Sphaerotheca pannosa* var. rosae. It has been demonstrated that double-capsulized nano silver, which is made up by combining silver ions with reducing agents, stabilizers, and physical techniques, may eradicate unwanted microbes from hydroponic systems and agricultural soils (Sonali *et al*., 2021).

Pest Management

Silver Nanoparticles are effective agents for the safe, non-toxic, and enhanced control of pests using pest management techniques. Pesticides based on nanotechnology effectively give target plants a high and appropriate dosage (Crystals, 2016). Traditional agricultural methods for creating nano-formulations, nano-pesticides, nano-sensors, and nano-fertilizers have been altered by the nanoscale use of agrochemicals (Singh *et al.,* 2021). Silver nanoparticle-based pesticide provides high doses of pesticides to the target plants (Lamsal *et al.,* 2011; Ragaei and Hasaan-Sabry, 2014). Microbes or plants can be the biological agents utilized in an environmentally friendly way of making silver nanoparticles. Since flavonoids found in plants are harmful to pests, the pesticidal activity of silver nanoparticles can significantly help control pests (Zahir *et al.,* 2012). The use of silver nanoparticles in insect pest control has been reported in their use in grasseries and rice weevil disease control. Given that stored rice treated with AgNPs remained uninfected even after two months of treatment, it suggests that AgNPs can potentially be utilized as a highly effective seed-preserving agent (Routray *et al.,* 2016). The application of nanoparticles made from plants plays a crucial role in pest control of stored grains. In contrast to the chemical-based production of nano-pesticides, this method offers a straightforward and environmentally friendly approach to development (Chen *et al*., 2019). Silver nanoparticles are employed for the delivery of agricultural chemicals to their intended destinations (Gour *et al*., 2019). During the storage stage, grains are mostly infested by *Tribolium castaneum* and have become resistant to most chemical pesticides. According to recent studies, 25 ppm, 75 ppm, and 100 ppm of silver nanoparticles and malathion were put into a disk. AgNPs and malathion both gave mortality rates of 75% and 95% at 75 ppm. The efficacy of malathion-based AgNPs against *Tribolium castaneum* was confirmed through tests for mortality, repellent action, anti-feedant activity, and deterrent effects on egg-laying. AgNPs have shown promise in effectively combating pests and insects (AS, 2019). AgNPs have larvicidal and bactericidal effects and are mostly synthesized from Shewanella algae bangaramma, a marine microbe. The 95% confidential limit for the LC50 and LC90 values was highest for III-instar Burmeister larvae (*Lepidiota mansueta*) at 4.529 mg/mL (2.478–5.911) and 9.580 mg/mL (7.528–14.541), respectively. The exposed groups displayed significantly higher larval mortality at all concentrations ($p < 0.0001$). Additionally, AgNPs showed a high maximum pupal death rate (77.44%) and high larval mortality rates (78.49% and 72.70%). Testing on mosquito larvae revealed LC50 values of 35.48 ppm for *C. quinquefasciatus* and 47.44 ppm for *A. aegypti*. Utilizing *L. nepetifolia* for AgNP production presents an eco-friendly approach to combat insect pests (Sajad *et al.,* 2023).

Uses of AgNPs in the Food Industry

Nanoparticles, with their unique properties, have found extensive applications in the preparation, preservation, packing, and processing of food. Historically, the greater part of nanotechnology research has focused on robotics, medicine, and electronics. The knowledge acquired in these fields may be applied to enhance agricultural and food products. For instance, nanotechnology could be harnessed for the conservation of the environment, such as purification of water, ensuring food safety by detecting pesticides and microbes, and enhancing nutrition delivery through "Conventional and Nano-Based Water Technologies" (Roco, 2003; Chau, 2007). There is a global increase in the availability of commercial foods and dietary supplements that contain additional nanoparticles. This has led to the advancement of nutritional supplements and nanoceuticals, which appear to be a rapidly growing field (Chen *et al*., 2006). The main strategy involves creating nanosized materials or carriers to improve the absorption and subsequently the bioavailability of other compounds such as vitamins, minerals, nutrients, or phytochemicals. These compounds might be applied either as liquids in drinks, added to solid foods, or applied directly to mucosal surfaces. The important considerations are whether the carriers and the contents that are encapsulated are regularly absorbed, digested, and metabolized. Thus, it is crucial to determine the absorption and metabolism of the material's nanoform and whether higher absorption levels raise new problems. In this case, encapsulation aims to optimize bioavailability rather than merely raise it (Van-Amerongen *et al*., 2005; Ulijn, 2007).

The following are the diverse applications of nanoparticles and their effects on food safety, sustainability, and quality in the food sector.

Food Processing Using Nanoparticles

Food processing is the process of preserving food by turning it into a consumable state using a variety of methods and techniques. These procedures and approaches are designed to keep microbes out of the food while preserving its flavour and quality (Fellows, 2009). The food industry requires advanced technologies to maintain its competitive edge in delivering culinary items that are flavourful, original, fresh, and convenient. The use of nanotechnology emerges as a solution to meet these demands (Chaudhry, 2009). Nanoparticles are employed in food processing techniques to improve efficiency, functionality, and nutritional value in the following ways;

Nanoemulsion

In food processing, nanomaterials are techniques that incorporate the use of nutraceuticals, the fortification of minerals and vitamins, the utilization of gelation as well as thickening agents, nutrient delivery, and the nanoencapsulation of tastes (Pradhan *et al*., 2015). For example, the solubility and bioavailability of lipophilic bioactive chemical formulations of food supplements that include antioxidants and vitamins are improved by nanoemulsions (McClements, 2018). Two or more liquids combined (oil and water, for example) that are difficult to mix are called an emulsion. As a result, a nanoemulsion is defined as an emulsion having scattered droplet diameters of 500 nm or less. According to McClements and Decker (2000), functional substances can be encapsulated within the droplets of nanoemulsions, hence facilitating a decrease in chemical degradation.

Emulsions with nanostructured layers

Emulsions with nanostructured layers are utilized to improve the sensory qualities and health benefits of processed foods. Nanostructured ingredients, such as nanofibers and nanocapsules, allow strategic delivery of nutrients, taste compounds, bioactive agents, etc., thereby enhancing overall quality of the products (Williams and Barry, 2018).

Polymer-based Bioparticles

In the making of nanoscale particles, food-grade biopolymers like proteins and polysaccharides can be employed. Aggregative (net attraction) or segregative (net repulsion) interactions can cause a single biopolymer to fragment into smaller nanoparticles. These Functional chemicals can be encapsulated in nanoparticles and released in response to particular environmental stimuli. One common component of several biodegradable biopolymeric nanoparticles is polylactic acid (PLA). PLA has limitations because it remains isolated in the liver and kidneys and is quickly removed from the bloodstream. Nevertheless, PLA is frequently used to encapsulate for the administration of medications, vaccinations, and proteins. For PLA to be effective as a nanoparticle, which transports active ingredients to different parts of the body, it requires an associating substance like polyethene glycol (Krishnakumar, 2019).

Nanolaminates

Nanolaminates are an emerging nanoscale technology with significant potential for the food industry, alongside nanodispersions and nanocapsules. A nanolaminate is an extremely thin food-grade sheet with dimensions that are linked chemically or physically, usually ranging from 1 to 100 nm per layer. Comprising more than two layers of material at the nanoscale, nanolaminates offer several advantages in producing edible films and hold considerable promise for various applications in the food sector (Ravichandran, 2010). Edible coatings are commonly utilized on a diverse range of consumables such as chocolates, meats, fruits, vegetables, baked goods, and French fries (Morillon *et al.,* 2002; Cagri *et al.,* 2004; Cha and Chinnan, 2004; Rhim, 2004). Incorporating these nano-edibles into food items serves multiple functions, including improving texture, transporting nutrients, antioxidants, flavours, colours, and antimicrobials, as well as providing resistance against moisture, fats, and gases. In addition, the addition of nanoparticles to various food items is a widespread practice aimed at prolonging shelf life and enhancing characteristics such as colour, flow, and stability during processing. For instance, anatase titanium dioxide is commonly employed as an agent for brightening and whitening in confectionery, certain cheeses, and sauces. Moreover, aluminosilicate compounds are frequently utilized as causes of granulation or powdering in processed meals (Alfadul and Elneshwy, 2010).

Nanocochleates

Attempts have been made within the food and beverage industry to include antioxidants and micronutrients as food ingredients. Nevertheless, throughout production and food storage, these antioxidants deteriorate. These compounds are shielded from deterioration by the nanocochleate delivery mechanism. For instance, the compounds found in most foods and wine, respectively, are called polyphenols and resveratrol, and they are rapidly damaged and oxidized when oxygen is present. By individually encasing each phospholipid wrap and protecting the interior nutrients from air and moisture, nanocochleates prevent early oxidation. The 50 nm coiled nanoparticles known as nanocochleates, created by Bio Delivery Sciences International, can be used to more effectively transport nutrients to cells, including vitamins, lycopene, and omega-3 fatty acids, without affecting the food's flavour or colour. The delivery vehicle is entirely harmless because it is composed of soy phosphatidylserine. For a variety of nutritional supplements, it offers a protective layer (Krishnakumar, 2019).

Nanoparticles in Food Packaging

Nanoparticles are extensively useful in packaging food materials because they possess exceptional barrier properties, antimicrobial activity, and sensorial attributes. In the current global economy, packaging is not only crucial for the efficient transportation and preservation of food and other consumer goods but also for facilitating customer communication and end-user convenience. According to Biswas and Dey (2015), nanotechnologies are useful in the food packaging industry for extending product shelf life, identifying rotting parts, and overall enhancement of product quality. One way they do this is by reducing gas flow across the product packaging. During distribution and storage, food products are shielded by packaging from both internal and external adverse circumstances, including dust, water vapour, microorganisms, fumes, viruses, and mechanical shock and vibrations. Several packaging systems have been developed to improve food quality. These include;

Intelligent Packaging

These are designed to examine the state of the packaged food contents and provide real-time information about their safety, freshness, and quality during storage and transportation. These systems typically incorporate sensors, indicators, or data carriers to interact with the products and their environment (Krishnakumar, 2019). In the food and beverage industries, biosensors play a crucial role in detecting specific ingredients, which include carbohydrates, lipids, vitamins, and proteins, while at the same time identifying and measuring chemical contaminants like heavy metals, antibiotics, and pesticides. They are also instrumental in identifying viruses and harmful bacteria such as Small Round Structured Viruses, Listeria, *Salmonella*, *Campylobacter*, *and E. coli* 0157. The objective is to detect ingested toxins, including those from shellfish causing paralysis or diarrhoea, mycotoxins, botulinum neurotoxins, and Staphylococcus enterotoxins. Additionally, the freshness of fish and fermentation processes are closely monitored (Fabiyi *et al*., 2024).

Improved Packaging (Active or Smart Packaging)

Using nanotechnology to create antimicrobial packaging is one of the most exciting developments in smart packaging. Nanomaterial-infused packaging can be "smart," meaning it can react to external factors, self-repair, or notify a customer about germs or pollution (Baeumner, 2004). They are increasingly employed as biosensors for physicochemical detection, combining biological components with temperature measurements. These advanced tools utilize nanoparticles' special characteristics (possession of high surface area, variable optical properties, and enhanced reactivity) for detecting environmental and biological parameters (Rhim *et al.,* 2013).

Electronic Tongue (e-tongue) and Electronic Nose (e-nose) Technology

By offering cutting-edge solutions for quality control, safety assurance, and shelf-life extension, these technologies have completely transformed the food packaging sector. To identify and evaluate volatile and non-volatile ingredients in food products, these technologies imitate human taste and olfactory systems. The food business will now use the electronic tongue and nose since these sensors are particularly good at identifying contaminants and evaluating the general quality of food (Vlasov *et al.,* 2000).

Nanoplastic Packing

Particles of plastic smaller than 100 nanometers are known as nanoplastics, and in recent years, they have raised serious environmental and human health issues. Although their existence in soils and oceans has attracted a lot of interest, there is growing concern about how they might affect food packaging. Numerous chemical companies are manufacturing translucent plastic film with nanotechnology for packaging that contains clay nanoparticles. The plastic is strengthened, made lighter, and more heat resistant by the incorporated nanoparticles, which protect the material from being heated by moisture, carbon dioxide, and oxygen. Additionally, according to Sorrentino *et al*. (2007), nanoplastics improve the mechanical qualities of packing materials, increasing their sturdiness and resistance to damage. Because of its potential to completely change how food is stored, conserved, and protected, the use of nanoplastics in packaging food has attracted much interest. Improving the preservation of food is one of the main benefits of using nanoplastic packaging (Gupta and Bashir, 2020). Conventional food packaging materials offer a basic barrier against pathogens, oxygen, and moisture, such as polyethylene and polypropylene. Nevertheless, by forming a more impermeable layer, nanoplastics can greatly strengthen these barriers. According to studies, by slowing down oxidation and microbiological growth, nanocomposite coatings can lead to an extension of the shelf life of perishable agricultural products (Silvestre *et al*., 2011).

Nanofibres and Nanotubes

The remarkable qualities of nanofibres and nanotubes (e.g., large surface area, mechanical strength, and barrier qualities) make them of high interest. Nanofibres are perfect for improving barrier qualities in food packaging due to their large volume-to-surface area ratio and their capacity to form a tight matrix. To preserve the freshness of food, these fibres can stop gases like carbon dioxide and oxygen from penetrating. To increase the shelf life of perishable items, it has been demonstrated that nanofibres derived from biopolymers (e.g., cellulose and chitosan) can strengthen package sheets mechanically and decrease their permeability (Yadav and Sharma, 2021). Nanotubes and fibres are innovative nanotechnology applications that are just beginning to affect the food business. There aren't many possible uses for nanofibres in the food business because they're typically not made of materials suitable for human consumption. These electrostatic force-produced nanofibres have minute diameters, ranging from 10 nm to 1,000 nm, which makes them ideal for use as a platform for bacterial growth (Krishnakumar, 2019). To further effectively prevent the growth of infections and spoilage organisms, antimicrobial compounds can be functionalized onto nanofibres. According to Han (2013) and Sorrentino *et al*. (2007), this active packaging strategy eliminates the need for chemical preservatives while maintaining food safety, thus satisfying consumer desire for more natural products.

Nanocomposites

Because these materials have relatively large surface-to-volume ratios and surface activities, nanocomposite films including nanoparticles like silver, titanium dioxide, and zinc oxide have shown increased characteristics. The shelf life of packaged foods can be prolonged by adding nanomaterials to compatible polymers, which can significantly improve the resulting nanocomposites' mechanical strength, enhanced thermal stability, increased electrical conductivity, UV light protection, and other material properties (Azeredo *et al*., 2019). Additionally, according to Jafari *et al* (2018), the use of nanoparticles integrated into packaging materials can impede microbial development, hence mitigating the risk of foodborne diseases and spoilage. Three primary categories can be used to categorize food packaging that utilizes nanotechnology (Silvestre *et al*., 2011; Duncan, 2011).

Nanoparticles for Food Safety Enhancement and Food Quality Monitoring

Nanoparticles exhibit potent antimicrobial properties, making them effective agents for controlling foodborne pathogens and preserving food quality. Silver nanoparticles, in particular, have garnered attention due to their extensive antibacterial action against fungi and viruses. Incorporating silver nanoparticles into food packaging materials or directly into food matrices can prevent the growth of microorganisms, thereby reducing the possibility of foodborne infections and using chemical preservatives (Duran *et al.,* 2016). Another possible application of nanotechnology in the food business is the use of nanoparticles to create nanosensors and nano sieves for the detection of food contaminants and pathogens in food systems. Customized nanosensors have been made for food analysis, water quality, flavours and colours, and medical diagnostics (Li and Sheng, 2014). By identifying pollutants, pathogens, and spoilage indications with exceptional sensitivity and specificity, nanosensors are essential for maintaining the safety and quality of food. Rapid and precise identification of hazardous compounds in food samples can be achieved through functionalized nanoparticles like carbon nanotubes and quantum dots. These nanosensors can detect trace levels of contaminants, allergens, and adulterants, enabling real-time monitoring throughout the food value chain (Raghu *et al.,* 2020).

Nano-sized Additives, Nutraceuticals and Nanoencapsulation

In functional foods, nutritional supplements, and nutraceuticals containing nanosized components and additives such as vitamins, antioxidants, antimicrobials, and preservatives, AgNP may enhance taste, absorption, and bioavailability (Momin *et al*., 2021). Protosterols, beta-carotene, lycopene, and other nutraceuticals are among those contained in the carriers, which are utilized in healthful diets to stop cholesterol from building up (Mozafari *et al*., 2006). Liposomes, micelles, protein-based carriers, and other nano-sized carrier systems or nanocapsules have been applied to nutritional supplements, and nano-food additives, masking unwanted taste, improving bioavailability, and improving the emulsifiers and surfactants are not required for the dispersion of insoluble additives (Morris, 2011; Cushen *et al*., 2012; Duran and Marcato, 2013). AgNPs are used in nanoencapsulation, which encloses food additives in a polymer nanocomposite for controlled release, such as polylysine-octenyl succinic anhydride (Sekhon, 2010). Additionally, it has been claimed that food additives, enzymes, antimicrobials, and nutraceuticals can all be delivered at the nanoscale using lipid-based nanoencapsulation techniques as those employed in nanoliposomes, nanocochleates, and archaeosomes (Mozafari *et al*., 2006; Mozafari *et al*., 2008). Probiotics can now be nanoencapsulated to target a particular GI tract region (Vidhyalakshmi *et al*., 2009). Preservatives and additives to enhance flavour or taste have been made using inorganic nano-sized additives and composites (e.g., AgNP). The addition of food-grade polypeptide Polylysine as an antioxidant to prevent oil from oxidizing is an example of nanoparticles. Due to their smaller size than phytoglycogenoctenyl succinate nanoparticles, these Polylysine nanoparticles can fill in the spaces left by phytoglycogenoctenyl succinate nanoparticles (Scheffler *et al*., 2010). Vargas *et al*. (2014) provided design details for a silver nano-coating that will be utilized in the nanoencapsulation process as a carrier of functional components. Chitosan-based edible nanoparticle films are produced by combining nanoparticles derived from nanosilver or silver zeolite (Rhim *et al*., 2006). In animal feeds, Ag nanocapsules can be developed to incorporate nano additives, antimicrobials, and detoxifying agents like mycotoxin-binding. Another application of AgNP in agriculture is the detection of animal diseases using nanosensors. Nanopesticides, such as those comprising pristinely designed nanoparticles including oxides of metals, metal itself, and nano clays, have been produced recently using nanocapsules and nanoemulsions (Kah and Hofmann, 2014; Kookana *et al*., 2014).

Conclusion

Nanoparticles have the potential to significantly enhance food quality, safety, and sustainability along the whole food supply chain. Nanoparticles are still the driving force behind innovation in the food business, from cutting-edge processing methods to sophisticated sensing technology and creative packaging solutions. They are essential instruments for overcoming current packaging material-related difficulties in nanotechnology. This development will benefit both food farmers and consumers by improving food quality, safety, security, and shelf life. Precautionary measures should be taken, though, and there is a need for additional study, especially about movement patterns on the potential impacts of food-borne nanoparticles on the environment and public health. Only by addressing protection as well as regulatory issues can a sustainable packaging solution be developed to guarantee the socially and economically responsible, long-term, and sustainable adoption of nanotechnology applications in food.

References

Abbaszadegan, A., Ghahramani, Y., Gholami, A., Hemmateenejad, B., Dorostkar, S., Nabavizadeh, M. and Sharghi, H. (2015). The effect of charge at the surface of silver nanoparticles on antimicrobial activity against gram-positive and gram-negative bacteria:

Alfadul, S.M. and Elneshwy, A.A. (2010). Use of nanotechnology in food processing, packaging, and safety – review. *African Journal of Food Agriculture Nutrition and Development*, 10(6), 2719-39.

Al-Huqail, A.A., Hatata, M.M., Al-Huqail, A.A. and Ibrahim, M.M. (2018). Preparation, characterization of silver phyto nanoparticles and their impact on the growth potential of *Lupinustermis L*. seedlings. *Saudi journal of biological sciences*, *25*(2), 313-319.

Ali, A., Zafar, H., Zia, M., Ul-Haq, I., Phull, A.R., Ali, J.S. and Hussain, A. (2011). Synthesis, characterization, applications, and challenges of iron oxide nanoparticles. *Nanotechnology, Science and Applications,* 4, 7–21.

Alloway, B. (2008). Micronutrient deficiencies in global crop production*, Springer Netherlands*, 329-334. doi: 10.1007/978-1-4020-6860-7.

Amin, H. H. (2020). Biosynthesized silver nanoparticles using *Ulvalactuca* as a safe synthetic pesticide (in vitro). *Open Agriculture.* 5. 291–299.

Anith, R., Jose,D., Devina, M., Arulananth, T.S.and Nagaraju, S. (2022). Characterization Analysis of Silver Nanoparticles Synthesized from *Chaetoceros calcitrans*. *Journal of Nanomaterials,* 2022, 15. https://doi.org/10.1155/2022/4056551

Arruda, S.C.C., Silva, A.L.D., Galazzi, R.M., Azevedo, R.A. and Arruda, M.A.Z. (2015). Nanoparticles applied to plant science: A review. *Talanta,* 131, 693–705.

A.S, A.A. (2019). Comparative bioassay of silver nanoparticles and malathion on infestation of red flour beetle, *Tribolium castaneum*. *The Journal of basic and applied zoology*, 80, 1-10.

Azeredo, H.M.C., Otoni, C.G., Correa, D.S., Assis, O.B.G., de Moura., M.R. and Mattoso L.H.C (2019). Nanocomposite Packaging Materials for Food Applications: An Overview. *Food Research International*, 123, 105-120.

Babu, M., Devi, V., Ramakritinan, C.M., Umarani, R., Taredahalli, N. and Kumaraguru, A. K. (2013). Application of biosynthesized silver nanoparticles in agricultural and marine pest control. *Current Nanoscience,* 10, 374–381.

Baeumner, A. (2004). Nanosensors identify pathogens in food. *Food Technology 58*, 51–52, 54–55.

Banerjee, K. and Ravishankar Rai, V. (2022). Silver nanoparticles synthesis mechanisms. *In Green Synthesis of Silver Nanomaterials.Elsevier,* 2022, 607–625.

Bhattacharyya, A., Prasad, R., Buhroo, A.A., Duraisamy, P., Yousuf, I., Umadevi, M., Bindhu, M.R., Govindarajan, M. and Khanday, A.L. (2016). One-pot fabrication and characterization of silver nanoparticles using *Solanumlycopersicum:* an eco-friendly and potent control tool against rose aphid, *Macrosiphumrosae*, *Journal of Nanoscience,* 2016, 1–7.

Biswas, P.K. and Dey, S. (2015). Effects and applications of silver nanoparticles in different fields. *International. Journal of Recent Scientific Research,*

6. 5880–5883.
Cagri, A., Ustunol, Z. and Ryser, E.T. (2004). Antimicrobial edible films and coatings. *Journal of Food Protection 67*, 833–848.
Cha, D.S. and Chinnan, M.S. (2004). Biopolymer-based antimicrobial packaging: review. *Critical Review in Food Science and Nutrition 44*, 223–237.
Chau, C.F. (2007). The development of regulations for food nanotechnology. *Trends in Food Science and Technology 18*, 269–280.
Chaudhry, Q. (2009). Nanotechnology for Food Applications: Current Status and Consumer Safety Concerns, AAAS Annual Meeting: *Nanofood for Healthier Living*,16.
Chekli, L., Bayatsarmadi, B. and Sekine, R. (2016). Analytical characterisation of nanoscale zero-valent iron: a methodological review: *Analytical Chimica Acta*, 903, 13-35.
Chen, H., Weiss, J. and Shahidi, F. (2006). Nanotechnology in nutraceuticals and functional foods. *Food Technology,* 60, 30–36.
Chen, L., Li, X., and Liu, Y. (2020). Quantum Dots for Time-Resolved Biosensing. *Biosensors and Bioelectronics*, 28(5), 789-796.
Chen, X., Chen, Y., Zou, L., Zhang, X., Dong, Y., Tang, J., McClements, D.J. and Liu, W. (2019). Plant-based nanoparticles prepared from proteins and phospholipids consisting of a core-multilayer-Shell structure: fabrication, stability, and foamability. *Journal of Agriculture and Food Chemistry,* 67, 6574–6584. https://doi.org/10.1021/acs. jafc.9b02028.
Chowdappa, P. and Gowda, S. (2013). Nanotechnology in crop protection: status and scope. *Pest Management in Horticultural Ecosystems*, *19*(2), 131-151.
Costa, M.V. and Sharma, P.K. (2016). Effect of copper oxide nanoparticles on growth, morphology, photosynthesis, and antioxidant response in *Oryza sativa*. *Photosynthetica*, 54, 110–119.
Crystals, P. (2016). Nanotechnology for insect pests. *Researchgate*, 3, 528–545.
Cushen, M., Kerry, J., Morris, M., Cruz-Romero, M. and Cummins, E. (2012). Nanotechnologies in the food industry–Recent developments, risks and regulation. *Trends in food science and technology*, *24*(1), 30-46.
Dainelli, D., Gontard, N., Spyropoulos, D., Zondervan-van den Beuken, E. and Tobback, P. (2008). Active and intelligent food packaging: legal aspects and safety concerns. *Trends in Food Science and Technology,* 19(1), S103-S112.
Dimkpa, C.O., McLean, J.E., Martineau, N., Britt D.W., Haverkamp, R. and Anderson, A.J. (2013). Silver nanoparticles disrupt wheat (*Triticum aestivum L.*) growth in a sand matrix. *Environmental Science and Technology*, 47, 1082–1090.
Duncan, T.V. (2011). Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. *Journal of colloid and interface science*, 363, 1-24.
Duran, N. and Marcato, P.D. (2013). Nanobiotechnology perspectives. Role of nanotechnology in the food industry: a review. *International Journal of Food Science and Technology*, *48*(6), 1127-1134.
Duran, N., Picoli, S. U., Durán, M., and Andrade, P. F. (2016). Silver nanoparticles/silver chloride (Ag/AgCl) synthesized from Fusarium oxysporum acting against Klebsiella pneumoniae carbapenemase (KPC) and extended spectrum beta-lactamase (ESBL). *Front. Nanosci. Nanotechnol*, *2*(2), 107-110.
Durán, N., Durán, M., De Jesus, M.B., Seabra, A. B., Fávaro, W.J. and Nakazato, G. (2016). Silver nanoparticles: A new view on mechanistic aspects of antimicrobial activity. *Nanomedicine: nanotechnology, biology and medicine*, *12*(3), 789-799.
Fabiyi, O. A., Abiodun, O. A., Akintayo, A. O., and Bello, T. T. (2024). Sustainable Food Processing and Packaging: The Role of Nanotechnology. In *Sustainable Nanomaterials: Synthesis and Environmental Applications*, Springer Nature Singapore. 317-338.
Fathima, J.B., Pugazhendhi, A., Oves, M., and Venis, R. (2018). Synthesis of eco-friendly copper nanoparticles for augmentation of catalytic degradation of organic dyes. *Journal of Molecular Liquids*, 2018, 260, 1-8.
Fellows, P.J. (2009). Food Processing Technology: Principles and Practice. *Woodhead Publishing*.
Filipponi, L.S. (2010). Characterization methods. In: *NANOYOU Teachers Training Kit in Nanotechnologies.*
Fortunati, E., Peltzer, M., Armentano, I., Jiménez, A. and Kenny, J.M. (2013). Combined effects of cellulose nanocrystals and silver nanoparticles on the barrier and migration properties of PLA nanobiocomposites. *Journal of Food Engineering*, 118, 117-124.
Fortunati, E., Puglia, D., Luzi, F., Santulli, C., Kenny, J.M. and Torre, L. (2013). Binary PVA bio-nanocomposites containing cellulose nanocrystals extracted from different natural sources: Part I. *Carbohydrate polymers*, 97(2), 825-836.
Gomaa, N.A., Mahdy, A.M.M., Fawzy, R.N. and Ahmed G.A. (2021). "Green synthesis of silver nanoparticle by plant extracts to control tomato wilt disease caused by *Fusarium oxysporum f. sp. lycopersici*." *International Journal of Scientific*

Research and Sustainable Development, 4.3(2021), 1-14.

Gon, S., Faulkner, M.J. and Beckwith, J. (2006). In vivo requirement for glutaredoxins and thioredoxins in the reduction of the ribonucleotidereductases of *Escherichia coli*. *Antioxidants and redox signaling*, 8(5-6), 735-742.

González-Melendi P., Fernández-Pacheco, R., Coronado, M.J., Corredor, E., Testillano, P.S., Risueño, M.C., Marquina C., Ibarra M.R., Rubiales, D. and Pérez-de-Luque, A. (2008). Nanoparticles as smart treatment-delivery systems in plants: assessment of different techniques of microscopy for their visualization in plant tissues. *Annals of Botany,* 101, 187–195.

Gour, N., Upadhyaya, P. and Patel, J. (2019). Nanomaterials as Therapeutic and Diagnostic Tools for Controlling Plant Diseases. *Comprehensive Analytical Chemistry*, Elsevier B.V. 225-261. https://doi.org/10.1016/bs.coac.2019.04.003.

Gru`ere, G.P. (2012). Implications of nanotechnology growth in food and agriculture in OECD countries. *Food Policy,* 37, 191-198. https://doi.org/10.1016/j.foodpol.2012.01.001.

Gruyer, N., Dorais, M., Bastien, C., Dassylva, N. and Triffault-Bouchet G. (2013). Interaction between silver nanoparticles and plant growth. In: *International symposium on new technologies for environment control, energy-saving and crop production in greenhouse and plant factory* – greensys. Jeju, Korea, 6–11.

Gupta, R., Srivastava, S. and Singh, P. (2017). Silver Nanoparticles in Microbial Biosensing. *Sensors and Actuators B: Chemical*, 242(3), 963-970.

Gupta, R. K., and Bashir, T. (2020). Recent Advances in Nano Biodegradable Plastics for Sustainable Food Packaging: Future Prospects and Challenges. *Journal of Polymers and the Environment*, 28(9), 2408-2424.

Gurunathan, S., Park, J.H., Han, J.W. and Kim, J.H. (2015). Comparative assessment of the apoptotic potential of silver nanoparticles synthesized by Bacillus tequilensis and Calocybeindica in MDA-MB-231 human breast cancer cells: Targeting p53 for anticancer therapy. *International Journal of Nanomedicine*. 10, 4203–4222.

Güzel, R. and Erdal, G. (2018) Synthesis of Silver Nanoparticles. In Silver Nanoparticles Fabrication, Characterization and Applications; Maaz, K., Ed.; *InTech*: Sydney, Australia, 2018.

Han, J.H. (2005). Innovations in food packaging. Academic Press, (2nd ed). San Diego: CA

Han, J. H. (2013). Packaging for non-thermal processing of foods. John Wiley & Sons.

Heinlaan, M., Ivask, A., Blinova, I., Dubourguier, H. C. and Kahru, A. (2008). Toxicity of nanosized and bulk ZnO, CuO, and TiO2 to bacteria *Vibrio*fischeri and crustaceans *Daphnia magna* and *Thamnocephalus platyurus*. *Chemosphere*, 71(7), 1308-1316.

Iravani, S., Korbekandi, H., Mirmohammadi, S.V. and Zolfaghari, B. (2014). Synthesis of silver nanoparticles: Chemical, physical and biological methods. *Research in Pharmaceutical. Science,* 2014 (9), 385–406.

Jafari, S. M., Hoseinnejad, M., and Katouzian, I. (2018). Inorganic and metal nanoparticles and their antimicrobial activity in food packaging applications. *Critical reviews in microbiology*, 44(2), 161-181.

Jasim, B., Thomas, R., Mathew, J. and Radhakrishnan, E.K. (2016). Plant growth and diosgenin enhancement effect of silver nanoparticles in Fenugreek (*Trigonella foenum-graecum L.*). *Saudi Pharmaceutical Journal,* 25, 443–447.

Kah, M. and Hofmann, T. (2014). Nanopesticide research: current trends and future priorities. *Environment international*. *63*, 224-235.

Kanwar, R., Fatima, R., Kanwar, R., Javid, M. T., Muhammad, U. W., Ashraf, Z., and Khalid, A. (2021). Biological, physical, and chemical synthesis of silver nanoparticles and their non-toxic biochemical application: A brief review. *Pure and Applied Biology (PAB)*, *11*(2), 421-438.

Khalandi, B., Asadi, N., Milani, M., Davaran, S., Abadi, A.J.N., Abasi, E. and Akbarzadeh, A. (2017). A review on the potential role of silver nanoparticles and possible mechanisms of their actions on bacteria. *Drug research*, 11(02), 70-76.

Khan, S., Zahoor, M., Khan, R. S., Ikram, M., & Islam, N. U. (2023). The impact of silver nanoparticles on the growth of plants: The agricultural applications. *Heliyon*, *9*(6).

Khorrami, S., Zarrabi, A. and Khaleghi, M. (2018) Selective cytotoxicity of green synthesized silver nanoparticles against the MCF-7 tumor cell line and their enhanced antioxidant and antimicrobial properties. *International Journal of Nanomedicine*, 13, 8013-8024.

Kim, I., Lee, B.T., Kim, H.A., Kim, K.W., Kim, S.D. and Hwang, Y.S. (2016). Citrate-coated silver nanoparticles change heavy metal toxicities and bioaccumulation of Daphnia magna. *Chemosphere*, 143, 99-105.

Kim, K.D., Han, D.N. and Kim, H.T. (2004). Optimization of experimental conditions based on the Taguchi robust design for the formation of nano-sized silver particles by chemical reduction method. *Chemical Engineering Journal*, 2004,104, 55–61.

King, T., Osmond-McLeodb, M.J., Lesley L. and Duffyc, L.L. (2018). Nanotechnology in the food sector and potential applications for the poultry industry. *Trends in Food Science and Technology,* 72, 62–73.

Klueh, U., Wagner, V., Kelly, S., Johnson, A. and Bryers, J. (2000). Efficacy of silver-coated fabric to prevent bacterial colonization and subsequent device-based biofilm formation. *Journal of biomedical materials research*. 53, 621-31. 10.1002/1097-4636(2000)53:63.0.CO;2-Q.

Kookana, R.S., Boxall, A.B., Reeves, P. T., Ashauer, R., Beulke, S., Chaudhry, Q. and Van den Brink, P.J. (2014). Nanopesticides: guiding principles for regulatory evaluation of environmental risks. *Journal of agricultural and food chemistry*, 62(19), 4227-4240.

Korshed, P., Li, L., Liu, Z. and Wang, T. (2016). The molecular mechanisms of the antibacterial effect of picosecond laser-generated silver nanoparticles and their toxicity to human cells. *PLoS One*, 11(8), e0160078.

Krishnakumar. T. (2019). Nanotechnology in food processing and packaging presentation. *Nanotechnology*. 1–24. Doi: 10.13140/rg.2.2.30391.16805

Krishnaraj, C., Jagan, E.G., Ramachandran, R., Abirami, S.M., Mohan, N. and Kalaichelvan P.T (2012). Effect of biologically synthesized silver nanoparticles on *Bacopamonnieri*(Linn.) Wettst. Plant growth metabolism. *Process Biochemistry,* 47(4), 51–658.

Kuorwel, K., Cran, M.J., Orbell, J.D., Buddhadasa, S. and Bigger, S.W. (2015). Review of mechanical properties, migration, and potential applications in active food packaging systems containing nanoclays and nanosilver. *Comprehensive Reviews in Food Science and Food Safety*,14, 411-430.

Lamsal, K., Kim, S.W., Jung, J. H., Kim, Y.S., Kim, K.S. and Lee, Y.S. (2011). Application of silver nanoparticles for the control of *Colletotrichum species* In Vitro and Pepper Anthracnose Disease in the Field, *Mycobiology*, 39, 26.

Lee, H., Kim, S. and Park, J. (2018). Electrochemical Oxygen Sensors Using Platinum Nanoparticles. *Analytical Chemistry*, 90(14), 8765-8772.

Lee, J.H., Sung, J.H., Ryu, H.R., Song, K.S., Song, N.W., Park, H.M. and Yu, I.J. (2018). Tissue distribution of gold and silver after subacute intravenous injection of co-administered gold and silver nanoparticles of similar sizes. *Archives of Toxicology*, *92*, 1393-1405.

Li, W.R., Xie, X.B., Shi, Q.S., Zeng, H.Y., Ou-Yang, Y.S. and Chen, Y.B. (2010). Antibacterial activity and mechanism of silver nanoparticles on *Escherichia coli*. *Applied Microbiology and Biotechnology*, 8, 1115–1122.

Li, Z. and Sheng, C. (2014). Nanosensors for food safety. *Journal of Nanoscience and Nanotechnology,*14(1), 905-12.

Llorens, A., Lloret, E., Picouet, P.A., Trbojevich, R. and Fernandez, A. (2012). Metallic-based micro and nanocomposites in food contact materials and active food packaging. *Trends in Food Science and Technology*. 24, 19-29.

Lombardo, P.C., Poli, A.L., Castro, L.F., Perussi, J.R. and Schmitt, C.C. (2016). Photochemical deposition of silver nanoparticles on clays and exploring their antibacterial activity. *ACS applied materials and interfaces*, 8(33), 21640-21647.

Long, X., Li, Z., Lu, X., Guo, H., Chang, C., Zhang, Q. and Liu, J. (2019). Mechanical behaviour of sintered silver nanoparticles reinforced by SiC microparticles. *Materials of Science and Engineering:* A, *744*, 406-414.

Mallick, K., Witcomb, M.J. and Scurrell, M.S. (2004). Polymer stabilized silver nanoparticles: A photochemical synthesis route. *Journal of Material Science*, 2004(39), 4459–4463.

Mandal, D., Dash, S.K., Das, B., Chattopadhyay, S., Ghosh, T., Das, D. and Roy, S. (2016). Bio-fabricated silver nanoparticles preferentially target Gram-positive bacteria depending on cell surface charge. *Biomedicine and Pharmacotherapy*, *83*, 548-558.

Manimegalai, G., Kumar, S.S. and Sharma, C. (2011). Pesticide mineralization in water using silver nanoparticles. *International Journal of Chemical Sciences*, *9*(3), 1463-1471.

McClements, D.J. (2018). Advances in Nanotechnology for Food Materials and Food Processing. *Annual Review of Food Science and Technology*, 9, 395-424.

McClements, D.J. and Decker, E.A. (2000). Lipid oxidation in oil-in-water emulsions: Impact of molecular environment on chemical reactions in heterogeneous food systems. *Journal of Food Science*, *65*, 1270–1282.

Mirzajani, F., Askari, H., Hamzelou, S., Farzaneh, M. and Ghassempour, A. (2013) Effect of silver nanoparticles on *Oryza sativa* L. and its rhizosphere bacteria. *Ecotoxicology and Environmental Safety*, 88, 48–54

Momin, G.G. (2013). Experimental investigation of mixed convection with water-Al2O3 and hybrid nanofluid in inclined tube for laminar flow. *International Journal of Scientific and Technology Research*, 2(12), 195-202.

Momin, Y.H. and Yeligar, V.C. (2021). Synthesis of *Cocciniagrandis* (L.) Voigt extract's silver nanoparticles and its in-vitro antidiabetic activity. *Journal of Applied Pharmaceutical Science*, 11(8), 108-115.

Monteiro, J.F.H.L., Monteiro, F.C., Jurelo, A.R. and Mosca, D.H. (2018). Conductivity in (Ag, Mg)-doped delafossite oxide CuCrO2. *Ceramics International*, *44*(12), 14101-14107.

Morillon, V., Debeaufort, F., Blond, G., Capelle,M. and Voilley, A. (2002). Factors affecting the moisture permeability of lipid-based edible films: a review. *Critical Reviews in Food Science and Nutrition,42*, 67–89.

Morris, V.J. (2011). Emerging roles of engineered nanomaterials in the food industry. *Trends in biotechnology*, 29(10), 509-516.

Mozafari, M.R., Flanagan, J., Matia-Merino, L., Awati, A., Omri, A., Suntres, Z.E. and Singh, H. (2006). Recent trends in the lipid-based nanoencapsulation of antioxidants and their role in foods. *Journal of the Science of Food and Agriculture*, 86(13), 2038-2045.

Mukherjee, P., Ahmad, A., Mandal, D., Senapati, S., Sainkar, S. R., Khan, M. I., Parishcha, R., Ajaykumar, P.V., Alam, M., Kumar, R. and Sastry, M. (2001). Fungus-mediated synthesis of silver nanoparticles and their immobilization in the mycelial matrix: a novel biological approach to nanoparticle synthesis. *Nano letters*, *1*(10), 515-519.

Nakamura, S., Sato, M., Sato, Y., Ando, N., Takayama, T., Fujita, M., and Ishihara, M. (2019). Review: Synthesis and Application of Silver Nanoparticles (Ag NPs) for the Prevention of Infection in Healthcare Workers. *International Journal of Molecular Sciences,* 2019, 20, 3620

Nguyen, N. P. U., Dang, N. T., Doan, L., & Nguyen, T. T. H. (2023). Synthesis of silver nanoparticles: from conventional to 'modern ' methods—a review. *Processes*, *11*(9), 2617.

Pallavi, M.C.M., Srivastava, R., Arora, S. and Sharma, A.K. (2016). Impact assessment of silver nanoparticles on plant growth and soil bacterial diversity. *3 Biotechnolog*, 6, 1-10.

Polash, S.A., Saha, T., Hossain, M.S. and Sarker, S.R. (2017). *Journal of Advances in Biology Biotechnology*, 8, 149-162.

Poole, R.K. (2000). Introduction to light absorption: visible and ultraviolet spectra. *Oxford University Press*, Oxford.

PRadhan, N., Singh, S., Ojha, N., Shrivastava, A., Barla, A., Rai, V. and Bose, S. (2015) Facets of Nanotechnology as Seen in Food Processing, Packaging, and Preservation Industry, *BioMedical Research International*, *2015*(1), 365672.

Pugazhenthiran, N., Anandan, S., Kathiravan, G., Prakash, N.K.U., Crawford, S. and Ashokkumar, M. (2009). Microbial synthesis of silver nanoparticles by *Bacillus Sp*. *Journal of Nanoparticle Research*, 11(7), 1811-1815

Quinteros, M.A., Aristizábal, V.C., Dalmasso, P.R., Paraje, M.G. and Páez, P.L. (2016). Oxidative stress generation of silver nanoparticles in three bacterial genera and its relationship with the antimicrobial activity. *Toxicology in vitro*, *36*, 216-223.

Ragaei, M. and Hasaan-Sabry, A. (2014). *International Journal of Environmental Science and Technology*. 3, 528–545.

Raghu, H. V., Parkunan, T., & Kumar, N. (2020). Application of nanobiosensors for food safety monitoring. *Environmental Nanotechnology,* 4, 93-129.

Rai, M.K., Deshmukh, S.D., Ingle, A.P., and Gade, A.K. (2012). Silver nanoparticles: the powerful nanoweapon against multidrug-resistant bacteria. *Journal of applied microbiology*, 112(5), 841-852.

Ramesh, P.S., Kokila, T. and Geetha, D. (2012). Plant-mediated green synthesis and antibacterial activity of silver nanoparticles using *Emblica officinalis* fruit extract. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy,* 91, 234-238.

Rana, N.K., Mohanpuria, P., Kumar, V., and Yadav, S.K. (2010). A CsGS is regulated at the transcriptional level during developmental stages and nitrogen utilization in *Camellia sinensis* (L.) O. Kuntze. *Molecular biology reports*, 37, 703-710.

Rankic, I., Zelinka, R., Ridoskova, A., Gagic, M., Pelcova, P., and Huska, D. (2021). Nano/microparticles in conjunction with microalgae extract as novel insecticides against Mealworm beetles, Tenebrio molitor. *Scientific Reports*, *11*(1), 17125.

Ravichandran, R. (2010). Nanotechnology Applications in Food and Food Processing: Innovative Green Approaches, Opportunities and Uncertainties for Global Market. *International Journal of Green Nanotechnology: Physics and Chemistry*, 1(2), 72-96.

Rhim, J.W., Park, H.M., and Ha, C.S. (2013). Bio-nanocomposites for food packaging applications. *Progress in Polymer Science*, 38(10-11), 1629-1652.

Rhim, J.W. (2004). Increase in water vapor barrier property of biopolymer-based edible films and coatings by compositing with lipid materials. *Food Science and Biotechnology*, *13*, 528–535.

Rhim, J.W., Hong, S.I., Park, H.M. and Ng, P.K. (2006). Preparation and characterization of chitosan-based nanocomposite films with antimicrobial activity. *Journal of agricultural and food chemistry*, *54*(16), 5814-5822.

Rizzo, D. M., Lichtveld, M., Mazet, J. A., Togami, E., and Miller, S. A. (2021). Plant health and its effects on food safety and security in a One Health framework: four case studies. *One health outlook*, *3*(1), 6. https://doi.org/10.1186/s42522-021-00038-7.

Robertson, G. L. (2005). Food packaging: principles and practice. New York: *CRC Press*.

Roco, M.C. (2003). Nanotechnology: convergence with modern biology and medicine. *Current Opinion in Biotechnology 14*, 337–346.

Routray, S., Dey, D., Baral, S., Das, A. P. and Patil, V. (2016). Potentials of nanotechnology in insect pest control, *Progressive Research and International Journal*, 11, 903-906.

Roy, A. and Chatterjee, K. (2021). Theoretical and computational investigations into mechanobactericidal activity of nanostructures at the bacteria-biomaterial interface: a critical review. *Nanoscale*, 13(2), 647-658.

Roy, A., Bulut, O., Some, S., Mandal, A. and Yilmaz, M. (2019). Green synthesis of silver nanoparticles: Biomolecule-nanoparticle organizations targeting antimicrobial activity. *RSC Advances,* 9, 2673-2702.

Sajad, K., Muhammad, Z., Raham, S.K., Muhammad, I., and Noor, U.I. (2023). The impact of silver nanoparticles on the growth of plants: The agricultural applications. *Heliyon*. 9(6).

Salama, H.M.H. (2012). Effects of silver nanoparticles in some crop plants, common bean (*Phaseolus vulgaris* L.) and corn (*Zea mays* L.). *International Research Journal of Biotechnology,* 3(10), 190–197

Savithramma, N., Ankanna, S. and Bhumi, G. (2012). Effect of nanoparticles on seed germination and seedling growth of *Boswelliaovalifoliolata*an an endemic and endangered medicinal tree taxon. *Nano Vision,* 2, 61–68.

Scheffler, S.L., Wang, X., Huang, L., San-Martin Gonzalez, F. and Yao, Y. (2010). Phytoglycogenoctenyl succinate, an amphiphilic carbohydrate nanoparticle, and ε-polylysine to improve lipid oxidative stability of emulsions. *Journal of Agricultural and Food Chemistry*, 58(1), 660-667.

Sekhon, B. S. (2010). Food nanotechnology–an overview. *Nanotechnology, science and applications*, 1-15.

Servin, A., Elmer, W., Mukherjee, A., De La Torre-Roche, R., Hamdi, H, White, J.C., Bindraban, P., and Dimkpa, C. (2015) A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. *Journal of Nanoparticle Research,* 17, 1–21.

Shafiq, M., Anjum, S., Hano, C., Anjum, I. and Abbas, B.H. (2020). An overview of the Applications of Nanomaterials and Nanodevices in the Food Industry. *Foods*, 9(2), 148.

Shameli, K., Ahmad, M.B., Yunis, W.Z., Ibrahim, N.A., Darroudi, M., Gharayebi, Y. and Sedaghat, S. (2010) Synthesis of silver/montmorillonitenanocomposites using γ-irradiation. *International Journal of Nanomedicine*, 2010(5), 1067–1077.

Sharma, S., Sharma, N. and Kaushal, N. (2023) Utilization of novel bacteriocin synthesized silver nanoparticles (AgNPs) for their application in antimicrobial packaging for preservation of tomato fruit. *Frontiers in Sustainable Food Systems*, 7, 1072738. doi: 10.3389/fsufs.2023.1072738

Sharma, P., Bhatt, D., Zaidi, M.G.H., Saradhi, P.P., Khanna, P.K. and Arora, S. (2012) Silver nanoparticle mediated enhancement in growth and antioxidant status of *Brassica juncea*. *Applied Biochemistry and Biotechnology*, 167, 2225–2233

Silvestre, C., Duraccio, D. and Cimmino, S. (2011). Food packaging based on polymer nanomaterials. Progress in Polymer Science, 36(12), 1766-1782.

Singh, P., Kim, Y. J., Singh, H., Wang, C., Hwang, K. H., Farh, M.E.A. and Yang, D.C. (2015). Biosynthesis, characterization, and antimicrobial applications of silver nanoparticles. *International journal of nanomedicine*, 2567-2577.

Singh, A., Dhiman, N., Kar, A.K., Singh, D., Purohit, M.P., Ghosh, D. and Patnaik, S. (2020). Advances in controlled release pesticide formulations: Prospects for safer integrated pest management and sustainable agriculture. *Journal of hazardous materials*, 385, 121525.

Singh, R.P., Handa, R. and Manchanda, G. (2021). Nanoparticles in sustainable agriculture: an emerging opportunity. *Journal of Controlled Release*. 329, 1234–1248. https://doi. org/10.1016/j.jconrel.2020.10.051.

Siritongsuk, P., Hongsing, N., Thammawithan, S., Daduang, S., Klaynongsruang, S., Tuanyok, A. and Patramanon, R. (2016). Two-phase bactericidal mechanism of silver nanoparticles against *Burkholderiapseudomallei. PloS one*, *11*(12), e0168098.

Sonali, K., Kale, I., Gajanan, V., Parishwad, A.S.N., Husainy. Aishwarya P.S. (2021). Emerging Agriculture Applications of Silver Nanoparticles. *ES Food & Agroforestry,* 3, 17-22.

Sorrentino, A., Gorrasi, G., and Vittoria, V. (2007). Potential perspectives of bio-nanocomposites for food packaging applications. *Trends in Food Science & Technology*, 18(2), 84-95.

Thiruvengadam, M., Rajakumar, G. and Chung, I.M. (2018). Nanotechnology: current uses and future applications in the food industry. *3 Biotechnology,* 8, 74. https://doi.org/10.1007/s13205-018-1104-7

Tiede, K., Boxall, A. B., Tear, S. P., Lewis, J., David, H., &Hassellöv, M. (2008). Detection and characterization of engineered nanoparticles in food and the environment. *Food additives and contaminants*, *25*(7), 795-821.

Tripathi, D.K., Singh, S., Singh, S., Srivastava, P.K., Singh, V.P., Singh, S., Prasad, S.M., Singh, P.K., Dubey, N.K., Pandey, A.C. and Chauhan, D.K. (2017). Nitric oxide alleviates silver nanoparticles (AgNPs)-induced phytotoxicity in Pisum sativum seedlings. *Plant Physiology and Biochemistry*, *110*, 167-177.

Tripathi, D.K., Singh, V.P., Prasad, S.M., Chauhan, D.K., Dubey, N.K. (2015) Silicon nanoparticles (SiNp) alleviate chromium (VI) phytotoxicity in *Pisumsativum*(L.) seedlings. *Plant Physiology and 96,* 96,189–198.

Tsuji, K. (2001). Microencapsulation of pesticides and their improved handling safety. *Journal of Microencapsulation*, 18,137–147.

Ulijn, R.V.(2007). Bioresponsive hydrogels*. Materials Today,* 10, 40–48.

Valipour, H., Shafagh-Kolvanagh, J., GhassemiGolezani, K. and Alizadeh-Salteh, S. (2021). Improvement of yield-related traits of spring rapeseed in response to nano-superabsorbent and bio-fertilizers under water deficit conditions. *Journal of Plant Physiology and Breeding*, 11(2), 15-32.

Van-Amerongen, A., Barug, D. and Wageningen, M. L. (2005). Rapid Methods for Biological and Chemical Contaminants in Food and Feed.*Wagenigen Academic Publishers, the Netherlands.*

Vargas-Villagran, H., Romo-Uribe, A., Teran-Salgado, E., Domínguez-Díaz, M. and Flores, A. (2014). Electrospun polylactic acid non-woven mats incorporating nanoparticles. *Polymer Bulletin*, 71, 2437-2452.

Vidhyalakshmi, R., Bhakyaraj, R. and Subhasree, R. S. (2009). Encapsulation "the future of probiotics" a review. *Advances in Biological Research*, 3(3-4), 96-103.

Vinković, T., Novák, O., Strnad, M., Goessler, W., Jurašin, D.D., Paradiković, N., and Vrček, I. V. (2017). Cytokinin response in pepper plants (*Capsicum annuum L.*) exposed to silver nanoparticles. *Environmental Research,* 156, 10–18.

Vishwanath, R. and Negi, B. (2021). Conventional and green methods of synthesis of silver nanoparticles and their antimicrobial properties. *Current Research in Green and Sustainable Chemistry*, 2021, 4, 100205.

Vlasov, Y. G., Legin, A. V., Rudnitskaya, A. M., D'amico, A., & Di Natale, C. (2000). Electronic tongue - new analytical tool for liquid analysis on the basis of non-specific sensors and methods of pattern recognition. *Sensors and Actuators B: Chemical*, *65*(1-3), 235-236.

Williams, H. D. and Barry, B. W. (2018). Nanostructured Lipid Carriers (NLC) for Delivery of Natural Phenolic Compounds. *Pharmaceutical Research*, 35(7), 1-14.

Yadav, V., and Sharma, P. (2021). Nanofibers in food packaging: A review on recent developments. *Journal of Food Science and Technology*, 58(3), 789-798.

Yokesh, B. M., Janaki, D. V., Ramakritinan, C. M., Umarani, R., Nayimabanu, T. and Kumaraguru, A. K. (2014). *Current Nanoscience,* 2014(10). doi:10.2174/15734137113096660103.

You, C., Han, C., Wang, X., Zheng, Y., Li, Q., Hu, X. and Sun, H. (2012). The progress of silver nanoparticles in the antibacterial mechanism, clinical application, and cytotoxicity. *Molecular biology reports*, 39, 9193-9201.

Zahir, A. A., Bagavan, A., Kamaraj, C. (2012). *Journal of Biopesticides* 5, 95–102.

Zawadzka, A., Płóciennik, P., Strzelecki, J. and Sahraoui, B. (2014). Transparent amorphous zinc oxide thin films for NLO applications. *Optical Materials*, 37, 327-337.

Zhang, X., Wang, X., Chen, Z. and Zhao, J. (2019). Gold Nanoparticles as Temperature Sensors. *Journal of Nanotechnology Research*, 11(2), 456-463.

Zhao, C., Wang, B., Theng, B. K., Wu, P., Liu, F., Wang, S., and Zhang, X. (2021). Formation and mechanisms of nano-metal oxide-biochar composites for pollutants removal: A review. *Science of the Total Environment*, 767, 145305.

Zhou, Y. and Tang, R. (2018). Facile and eco-friendly fabrication of AgNPs coated silk for antibacterial and antioxidant textiles using honeysuckle extract. *Journal of Photochemistry and Photobiology B*, 178, 463-471.