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Effect of Nano-particles on plant growth and their applications in agriculture: A Review

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ABSTRACT

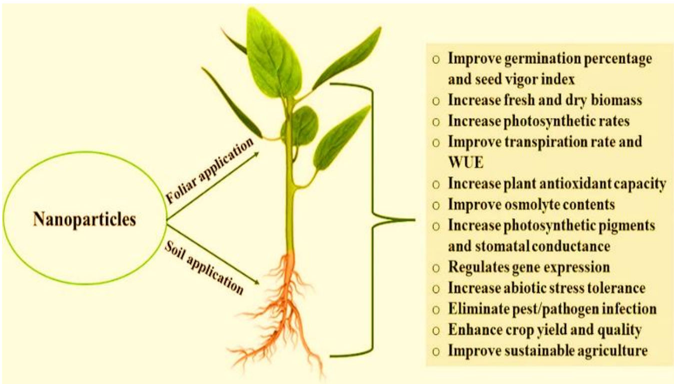
Nanotechnology opens a large scope of novel application in the fields of biotechnology and agricultural industries, because nanoparticles (NPs) have unique physicochemical properties, i.e., high surface area, high reactivity, tunable pore size, and particle morphology. Nanoparticles can serve as "magic bullets", containing herbicides, nano-pesticide fertilizers, or genes, which target specific cellular organelles in plant to release their content. Numerous studies suggest that nanotechnology will have major, long-term effects on agriculture and food production. Nanoparticles have enhanced reactivity due to enhanced solubility, greater proportion of surface atoms relative to the interior of a structure, unique magnetic/optical properties, electronic states, and catalytic reactivity that differ from equivalent bulk materials. The positive morphological effects of nanomaterials include enhanced germination percentage and rate; length of root and shoot, and their ratio; and vegetative biomass of seedlings along with enhancement of physiological parameters like enhanced photosynthetic activity and nitrogen metabolism in many crop plants. Additionally, this technology holds the promise of controlled release of agrochemicals and site targeted delivery of various macromolecules needed for improved plant disease resistance, efficient nutrient utilization and enhanced plant growth. Meanwhile, concerns have been raised about potential adverse effects of nanoparticles on biological systems and the environment such as toxicity generated by free radicals leading to lipid peroxidation and DNA damage. Generally, abiotic stresses have adverse impacts on plant growth and development which affects agricultural productivity, causing food security problems, and resulting in economic losses. To reduce the negative effects of environmental stress on crop plants, novel technologies, such as nanotechnology, have emerged. Implementing nanotechnology in modern agriculture can also help improve the efficiency of water usage, prevent plant diseases, ensure food security, reduce environmental pollution, and enhance sustainability.

Keywords: *Plant nutrition, Plant growth, Nanoparticles, crop yield, modern agriculture, nanotechnology, plant performance*

1. INTRODUCTION

The positive morphological effects of nanomaterials include enhanced germination percentage and rate; length of root and shoot, and their ratio; and vegetative biomass of seedlings along with enhancement of physiological parameters like enhanced photosynthetic activity and nitrogen metabolism in many crop plants. The foremost universal challenge on our planet is the question of establishing food security for a rapidly increasing population in the world. Predictions show that food demand is likely to rise from 59 to 98% for the world population reaching 9 billion by 2050 (Duro et al., 2020). Despite an increase of the world population particularly in developing countries, the global food supply interrupted by the expenditure of bio-resources for production of energy, manufacturing chemicals, high post farming loss, less value addition, inefficient distribution and marketing systems, and other factors (Barrett, 2021; Sekhon, 2014). Farmers throughout the world will focus on using new innovations and technologies for enhancing the production of crops through intensive and extensive agriculture. The current efforts further boosted through the use of nano-modified stimulants and precision farming. Agricultural efficiency, soil improvement, secure water use, distribution of food in stores, and its quality are basic factors of securing food that may be improved via advances in nanotechnology research (Ashraf et al., 2021; Sastry et al., 2011). Newer technology that will increase the production and reduce food wastage is important to maintain sustainable living standards of the nation and improve food security. Nanotechnology can provide a path for producing foods with outstanding quality in highly improved workable form along with induction of nutrients bioavailability. Many research investigations are focusing on increasing the application of nanotechnology for the production of crop and food processing (Abobatta, 2018; Axelos and Van De Voorde, 2017; Dasgupta et al., 2015; Peters et al., 2016). Increment in articles, intellectual property, and patents in nano-agriculture-based food with fresh research tendencies in the processing of food, nutraceutical distribution, packing, quality control, and serviceable food is a highly expanding field in nanotechnology research (Dasgupta et al., 2015). Nanotechnology is one of the promising areas to boost the availability of food and to manufacture newer products for beneficial purposes in agriculture, food, water, the environment, medicine, energy, and electronics. It is a developing and quickly growing region with new and exclusive applications in agriculture and food research (Sadeghi et al., 2017). Growing productivity and declining postharvest expenditure via better outcomes with the support of newer technical investigations with the help of nanotechnology and biotechnology in foodstuffs might be the best answer (Yadollahi et al., 2010). Few evolving areas regarding nanomaterials in agriculture are to reduce the number of spread chemicals, minimize nutrient losses in fertilization, and increased yield through pest and nutrient management (Prasad et al., 2017a).

Some of the emerging topics of nanotechnology for food can be largely improved in the aspects of smart delivery of nutrients, bioseparation of proteins, rapid sampling of biological and chemical contaminants, nanoencapsulation of nutraceuticals, solubilization, delivery (Ravichandran, 2010; Sozer and Kokini, 2009). Food nanotechnology comprises the application of nanocarrier methodologies to strengthen the bioactive ingredients to modify their biological accessibility and barrier against several chemical or environmental variations (Mozafari et al., 2008). It induces better sensory characteristics like color, flavor, and texture and enhances reliability in food (Kalita and Baruah, 2019). It also improved the captivation and biological convenience of nutraceuticals (Jafari and McClements, 2017) and drug delivery systems (Safari and Zarnegar, 2014). Nanotechnology is benefiting food industries as a novel food packing supplies with modified mechanical, fencing, and antimicrobial characteristics (Mustafa and Andreescu, 2020; Rossi et al., 2017; Duncan, 2011). Nanotechnology-based sensors for trace detection observing the condition of diet in terms of transportation and storing, and encapsulation of food modifiers or additive materials were other merits of the technology (Chaudhry et al., 2008). Nanotechnology-based applications have put forward the growing requirement of using nanoparticle in food biotechnology, science, food processing, food packaging, functional food development, food safety, detection of pathogens in food, and extended shelf-life of food and food foodstuffs (Singh et al., 2017). Nanomaterials perform very well in enhancing food security to support the development of food manufacturing industry. Depositing of food manufacturing equipment (via biofilm coating), nanofabricated filters, sieves and membranes, nanocomposite based and nanosized adsorbents and catalytic agents are also utilization areas for provision of assistance in the processing of food. Adding nanomaterials into the packing of food are supposed to modify the hindrance felt during materials packing and can help decrease the involvement of valued raw ingredients and waste production (Sozer and Kokini, 2009).



Sourses: Mohamed T. El-Saadony et* al*, 2022.

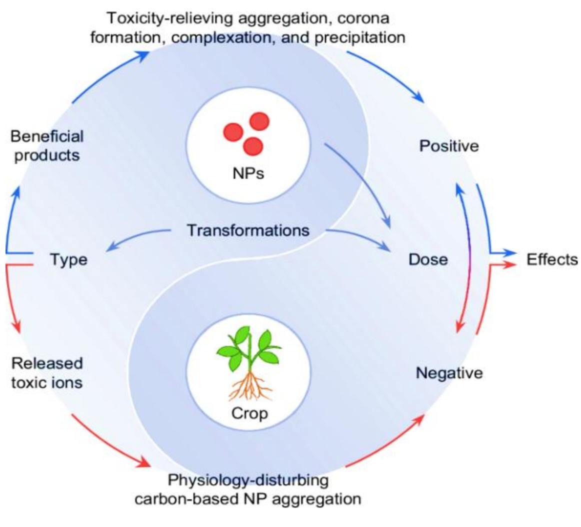
Fig 1: Effects of nanoparticles on plant health, growth performance and physiological parameters. WUE, water use efficiency.

2. NANO-FARMING IN AGRICULTURE:

Nanoparticle engineering is one of the latest technological innovations that demonstrate unique targeted characteristics with elevated strength. The term 'nanotechnology' was first coined by Norio Taniguichi, a professor at Tokyo University of Science, in 1974. Although, the term 'nanotechnology' has long been introduced in multiple disciplines, the idea that nanoparticles (NPs) could be of interest in agricultural development is a recent technological innovation, and is still under progressive development. Recent advancements in the fabrication of nanomaterials of different sizes and shapes have yielded their wide array of applications in medicine, environmental science, agriculture and food processing. Throughout history, agriculture has always benefited from these innovations. In continuation, as agriculture faces numerous and unprecedented challenges, such as reduced crop yield due to biotic and abiotic stresses, including nutrient deficiency and environmental pollution, the emergence of nanotechnology has offered promising applications for precision agriculture. The term precision agriculture or farming has emerged in recent years, meaning the development of wireless networking and miniaturization of the sensors for monitoring, assessing, and controlling agricultural practices. More specifically, it is related to the site-specific crop management with a wide array of pre- and post-production aspects of agriculture, ranging from horticultural crops to field crops. Recent advancements in tissue engineering and engineered nanomaterials-based targeted delivery of CRISPR (clustered regularly interspaced short palindromic repeats)/ Cas (CRISPR-associated protein) mRNA, and sgRNA for the genetic modification (GM) of crops is a noteworthy scientific achievement. Further, nanotechnology provides excellent solutions for an increasing number of environmental challenges. For example, the development of nanosensors has extensive prospects for the observation of environmental stress and enhancing the combating potentials of plants against diseases. Therefore, such continuous improvements in nanotechnology with special preference on the identification of problems and development of collaborative approaches for sustainable agricultural growth has remarkable potential to provide broad social and equitable benefits.

3. SOURCES AND SYNTHESIS OF GREEN NANOPARTICLES

Nanoparticles (NPs) are organic, inorganic or hybrid materials with at least one of their dimensions ranging from 1 to 100 nm (at the nanoscale). NPs that exist in the natural world can be produced from the processes of photochemical reactions, volcanic eruptions, forest fires, simple erosion, plants and animals or even by the microorganisms. The production of plant- and microorganism- derived NPs, has emerged as an efficient biological source of green NPs that draw an extra attention of scientist in recent times due to their eco-friendly nature and simplicity of production process compared to the other routes. For the exploitation of the green nanotechnology, a number of plant species and microorganisms including bacteria, algae and fungi are being currently used for NP synthesis. For example, *Medicago sativa* and *Sesbania* plant species are used to formulate gold nanoparticles. Likewise, inorganic nanomaterials, made of silver, nickel, cobalt, zinc and copper, can be synthesized inside live plants, such as *Brassica juncea, Medicago sativa and Heleanthus annus*. Microorganisms, such as diatoms, *Pseudomonas stuzeri*, *Desulfovibrio desulfuricans*, *Clostridium thermoaceticum* and *Klebsiella aerogens* are used to synthesize silicon, gold, zinc sulphide and cadmium sulphide nanoparticles, respectively. Although a large number of microorganisms are used to synthesize green NPs, fungi, mainly *Verticillium* sp., *Aspergillus flavus*, *Aspergillus furnigatus*, *Phanerochaete chrysosparium* and *Fusarium oxysporum* are considered to be the most efficient systems for the biosynthesis of metal and metal sulphide containing NPs. All NPs are three-dimensional (3D) objects. One dimensional (1D) NPs refers to the NPs that have 2 dimensions at the nanoscale and 1 dimension at the macroscale (nanowires, nanotubes), whereas two-dimensional (2D) NPs have 1 dimension at the nanoscale and 2 dimensions at the macroscale (nanolayers, nanofilms). Again, 3D NPs have 0 dimension at the nanoscale and 3 dimensions at the macroscale (nanoballs, nanoflowers), whereas zero-dimensional (0D) NPs are characterized by all 3 dimensions at the nanoscale.



Sourses: Linfeng Wei, et al, 2024

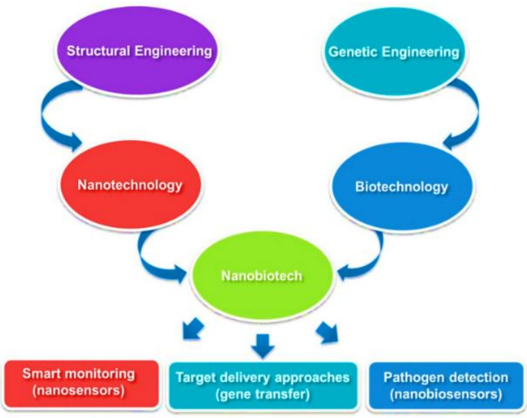
Fig 2: NPs and crops interact with each other. Additionally, the types and product doses of the transformations of NPs in crop systems play decisive roles in their effects on crops. Beneficial transformation products and transformations relieving the initial phytotoxicity of NPs and their transformation products have positive effects on crops. Toxic transformation products and NP transformations disturbing physiological processes in plants induce harmful phytotoxicity.

For instance, a rich variety of physical and chemical methods have been developed in favor of synthesis or fabrication of the zero-dimensional NPs with well-controlled dimensions. Zero-dimensional NPs, such as quantum dots have wide acceptability and application in light emitting diodes, solar cells, single-electron transistors as used in lasers. The synthesis of two-dimensional NPs, such as junctions (continuous islands), branched structures, nanoprisms, nanoplates, nanosheets, nanowalls, and nanodisks have become a crucial area in nano-engineering research. Such geometric structures of NPs have blown up the investigation and development of novel applications in sensors, photocatalysts, nanocontainers and nanoreactors. In contrast, three-dimensional NPs have recently attracted considerable research interest owing to their large surface area and other superior properties like absorption sites for all involved molecules in a small space which lead to a better transport of the molecules. Therefore, the improvement and development of novel technology for the production of NPs with their potential application have special significance, particularly in the development of sustainable agricultural and environmental systems.

4. NANO PARTICLE AS A NEW WINDOW FOR SUSTAINABLE AGRICULTURE:

Nanotechnology is considered as one of the key technologies in the twenty-first century that promises to advance traditional agricultural practices and offer sustainable development by improving the management and conservation tactics with reduced waste of agricultural inputs. The delivery systems of agrochemicals and organic molecules including transport of DNA molecules or oligonucleotides into the plant cells are important aspects of sustainable agricultural production as well as precision farming. In conventional methods, agrochemicals are generally applied to crops by spraying and/or broadcasting. As a result, a very low number of agrochemicals reaches the target sites of crops, which is much below the minimum effective concentration required for successful plant growth. The losses are due to leaching of chemicals, degradation by photolysis, hydrolysis and also by microbial degradation. For instance, in the case of the application of fertilizer, more emphasis should be made of the bioavailability of nutrients due to the chelation effects of soil, degradation by microorganisms, evaporation, over-application, hydrolysis, and run-off problems. In the case of pesticide applications, the efficacy enhancement with spray drift management is to be focused on. In order to ensure eco-friendly agricultural practices, the recent advancement of nanotechnology-based synthesis of slow or controlled release fertilizers, pesticides and herbicides has, therefore, received an extra attention in agriculture farming. With the passage of time, nanotechnology has gradually moved from the lab-based experimental trials to practical applications.

The aim of controlled delivery techniques is to release measured amount of necessary and sufficient quantities of agrochemicals over a period of time and to obtain the full biological competency with minimizing the loss and harmful effects. Nanoparticles offer the advantages of effective delivery of agrochemical due to their large surface area, easy attachment and fast mass transfer. For these reasons, micronic or submicronic particles are incorporated into the agrochemicals through several mechanisms, such as capsulation, absorption, surface ionic or weak bond attachments and entrapment into the nano-matrix of active ingredients. For example, the capsulation of potassium nitrate by graphene oxide films considerably prolongs the fertilizer release process and such a formulation seems to be possible at a relatively low cost under large scale production. Nanomaterials improve stability of agrochemicals and protect them from degradation and subsequent release into the environment, which eventually increase the effectiveness and reduce the quantities of agrochemicals.



Sourses: Yifen Shang, 2019

Fig 3: An overview of nanobiotechnology. Convergence of nanotechnology and biotechnology results in nanobiotech, which entails knowledge of structural engineering and genetic engineering. Nanobiotechnologies are used for different purposes in agriculture, including smart monitoring (nanosensors), target delivery of nucleic acid (gene transfer) and plant pathogen detection (nanodiagnostics). (Modified and redrawn from references

5. CLASSIFICATION OF NANOMATERIALS

Nanoparticles are categorized into their respective categories based on their morphology, which refers to their structure, as well as their size and shape. The nanoparticles listed below are some of the most significant types currently known.

5.1. Organic Nanomaterials

The different types of organic nanoparticles, some of which are micelles, dendrimers, liposomes, nanogels, polymeric NPs, and layered biopolymer. Certain organic nanoparticles, such as micelles and liposomes, have a hollow sphere, and they are non-toxic and biodegradable. Organic nanoparticles can also be broken down naturally. This name is also used to refer to nanocapsules, which are extremely sensitive to light and heat. Due to the fact that organic nanoparticles exhibit these properties, they are an excellent option for the transportation of pharmaceuticals. Nanoparticles are also frequently used in the process of transporting target medications to their intended locations. Organic nanoparticles are also sometimes referred to by the label polymeric nanoparticles. The nanosphere or nanocapsule is the most famous form of polymeric or organic nanoparticles. The matrix particles have a solid sphere of mass and adsorb other molecules at the outer boundary of spherical surface. Particles encapsulated the solid mass in the later case.

5.2. The displaying the organic nanoparticles.

Magnetic nanoparticles (mNPs) are one of the most significant inorganic nanomaterials. A magnetic core (*e.g.* maghemite (g-Fe_2O_3) or magnetite (Fe_3O_4)) is generally present. Other metals, such as nickel and cobalt, are also employed, although their applications are limited due to their toxicity and oxidation vulnerability. Ferritin, a type of protein, is where the vast majority of iron is kept in the human body. Iron oxide mNPs have the ability to digest excess iron and restore the supply in the human body. There is a continuous presence of these cationic mNPs in the endosomes for a considerable amount of time. This continues to be the case over and overAfter that, during the postcellular absorption process that takes place in the endosome and the lysosome, elemental components like iron and oxygen are brought into the body's storage, where hydrolytic enzymes either digest them or cause their destruction. In the human body, homeostasis is the process through which iron levels are maintained and adjusted. Adsorption, excretion, and storage are all processes that contribute to this process. Iron oxide nanoparticles help the body digest any excess iron that may be present. Iron is essential in almost all biological tissues, yet it has a low bioavailability. In certain circumstances, it can damage the cells when they are in the form of free iron or when it is not associated with haemoglobin. Additionally, it can be harmful to cells when it is present alone. The displaying the inorganic nanomaterials. Magnetic nanoparticles (mNPs) are one of the most significant inorganic nanomaterials. A magnetic core (*e.g.* maghemite (g-Fe_2O_3) or magnetite (Fe_3O_4)) is generally present. Other metals, such as nickel and cobalt, are also employed, although their applications are limited due to their toxicity and oxidation vulnerability. Ferritin, a type of protein, is where the vast majority of iron is kept in the human body. Iron oxide mNPs have the ability to digest excess iron and restore the supply in the human body. There is a continuous presence of these cationic mNPs in the endosomes for a considerable amount of time. This continues to be the case over and over After that, during the postcellular absorption process that takes place in the endosome and the lysosome, elemental components like iron and oxygen are brought into the body's storage, where hydrolytic enzymes either digest them or cause their destruction. In the human body, homeostasis is the process through which iron levels are maintained and adjusted. Adsorption, excretion, and storage are all processes that contribute to this process. Iron oxide nanoparticles help the body digest any excess iron that may be present. Iron is essential in almost all biological tissues, yet it has a low bioavailability. In certain circumstances, it can damage the cells when they are in the form of free iron or when it is not associated with haemoglobin. Additionally, it can be harmful to cells when it is present alone. The displaying the inorganic nanomaterials.

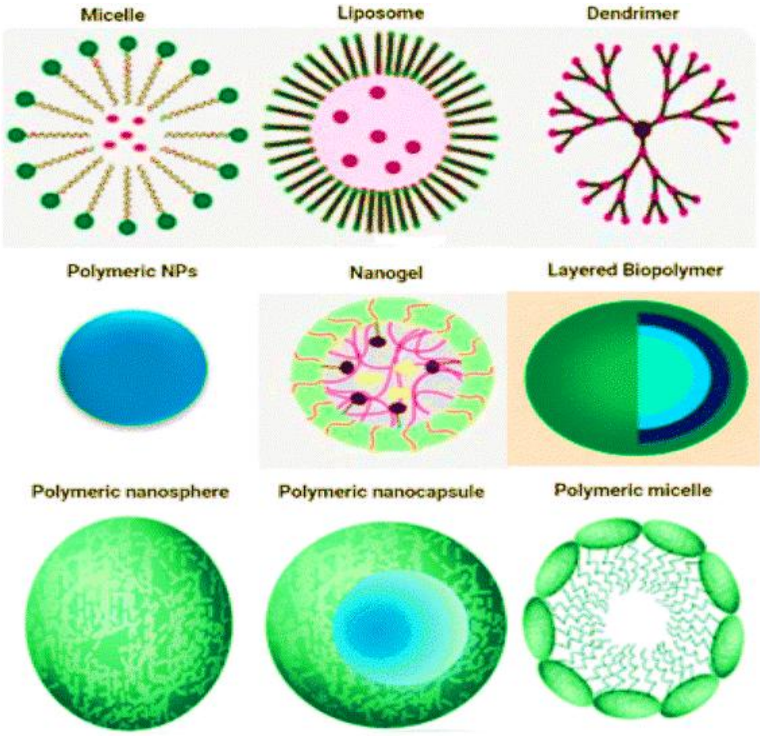


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Fig 4: The Schematic diagram of Organic Nano particles

5.2.1. Elements. Therefore, it is possible to classify nanoparticles into two groups: metallic nanoparticles that provide essential microelements and metallic nanoparticles that do not provide essential elements.

Inorganic nanoparticles that provide essential microelements for plants can be highlighted.

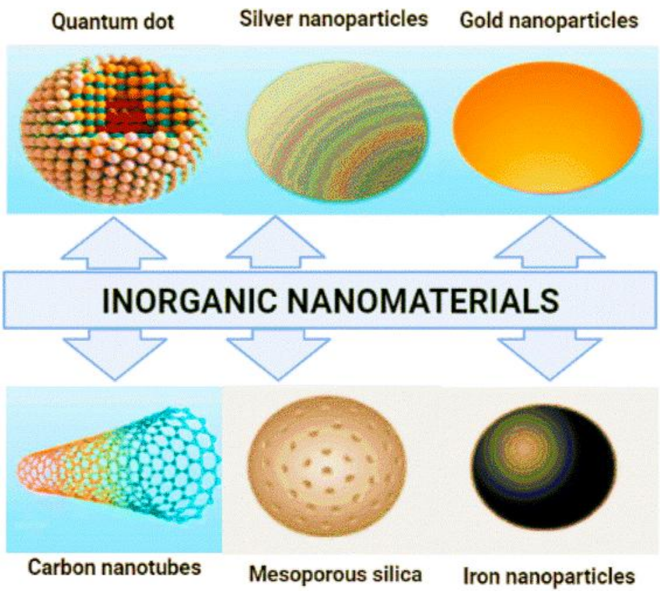

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Fig 5: Inorganic nanoparticles, metal and metal oxide nanoparticles are categorized as inorganic nanoparticles.

5.2.2. Zinc nanoparticles. Zn is an essential element for plants. Although some studies have indicated that photosynthetic parameters can be affected (e.g., Wang et al., 2016; Pedruzzi et al., 2020), these adverse impacts are usually size-dose dependent. In general, Zn has the po- tential to increase the biosynthesis of photosynthetic pigments, plant biomass and defense mechanism (e.g., improving the antioxidant response system and a reduction on reactive oxygen species and lipid peroxidation) (e.g., Singh et al., 2016; Faizan et al., 2018; ReddyPullagurala et al., 2018; Salam et al., 2022a). So its application can be very useful, especially under abiotic stress such as metal contamination (Boonchuay et al., 2013; Reddy Pullagurala et al.,2018; Iqbal et al., 2020; Salam et al., 2022a).

5.2.3. Copper Nano-Particles. Cu is an essential element for plants. De- ficiencies of this element can occur in certain soils and with certain crops. Moreover, its role as an antifungal is well known, so it is applied to many crops, mainly vineyards and fruit trees. (Va´zquez-Blanco et al., 2023). Applying foliarly Cu nano- particles improves important plant processes such as increasing abscisic acid content in tomatoes (Lo´pez-Vargas et al., 2018) or improving photosynthesis and resistance under abiotic stress.

5.2.4. Iron Nano-Particles. Fe nanofertilizers can replace traditional fertil- izers, improving the production and quality of these products (Jeyasubramanian et al., 2016). For example, Fe nanoparticle application improves root and stem growth and biomass produced in Arachis hypogaea (Rui et al., 2016). Similarly to Zn nanoparticles, Fe nanoparticles can also improve plant photosynthesis and reduce oxidative stress for crops grown on contaminated soils (Khan et al.,2020).

5.2.5. Nickel Nano-Particles. These nanoparticles have been tested mainly as effective against plant diseases and mixed with Fe nanoparticles on several occasions (Nazarova, 2022; Zhou et al., 2023). Among the inorganic nanoparticles that do not provide essential microelements for plants, Ag and Ti nanoparticles should also be high- lighted. Other nanoparticles are also used, although to a lesser extent, such as Au, Se, Ce, Si and Al nanoparticles, which can positively affect certain plants that help improve the productivity or safety of agricultural products.

5.2.6. Silver Nano-Particles. They have healing effects on different microbial diseases and a positive effect on plant growth, even at low concen- trations (±20 mg kg—1) (Salama, 2012).

5.2.7. Titanium Nano Particles. Ti nanoparticles applied to soil improve soilsalinity, increasing plant leaf length and dry weight (Fatima et al.,2021). They also favor the germination of some seeds, as reported for commercial crops such as onion (Laware and Raskar, 2014), spinach (Zheng et al., 2005) or mung bean (Mathew et al., 2021).

6. PRINCIPLES OF NANO TECHNOLOGY

Nanotechnology means the "synthesis, designing, characterizing, and utilization of assemblies, tools, and systems via directing the morphology and size variation at nanometer level from 1 - 100 nm" (Yadollahi et al., 2010). For your reference, one nanometer-scale means one-billionth (10^{-9}) of part of one meter which implies that the application of the technology at this size. Nanoscience and nanotechnologies considered as innovative attitudes in developmental research related to the learning of marvels and operation of substance at atomic, molecular, or macromolecular levels, at which stage their properties are considerably varied to those at bulk level (Potocnik, 2005). Here, the biological, chemical, and physical characteristics of resulting products are fundamentally different from those of bulk material. The investigation of properties at nanoscale gives birth to modified properties that could be used manufacturing novel materials with modified structures, newer tools, and products that could perform more efficiently.

The differently displayed properties of materials at nano scale provided newer properties such as more strength, improved optical properties, modified antimicrobial potential, and outstanding superconductive nature (Axelos and Van De Voorde, 2017). They can adopt shapes like nanotubes, nanoparticles, nanofibers, fullerenes, nanosheets, and nanowhiskers (Cushen et al., 2012). As per published European Commission (EC) recommendation, a nanomaterial is defined as "natural, incidental, or industrial material with particles, in an unbound state or in the form of aggregate or agglomerate where 50% or more of the particles in the number and size distribution, one or more than one dimensions lies in the range of 1–100 nm" (Potocnik, 2011)..

7. APPROACHES OF NANO-TECHNOLOGY

Nanotechnology can be applied via two opposite approaches that are "bottom-up" or "top-down" approach even in food technology. The top-down approach can be employed via the physical method undertaken for food and agriculturally based materials. Production of nanomaterials at a commercial scale presently employs mainly the ''top-down" approach, where nanoscale materials are synthesized by size decrease of bulk precursors, via milling technique, nanolithography, or using precision engineering (De Azeredo, 2009; Sozer and Kokini, 2009). Dry milling protocol is employed to get grain flour with reduced size and hence more water-retaining ability. The top-down approach can enhance the antioxidant properties of green tea via size decreasing procedure (Shibata, 2002). According to a report, powdered green tea with 1000 nm size has higher digestion of nutrients and results in the enhanced ability for dismutase enzyme with enhanced removal of oxygen and hence elevated antioxidant activity (Sanguansri and Augustin, 2006). Another procedure called homogenization broadly used for dairy work regarding size reduction in case of globules, vaporization, and laser application associated with cooling is also supposed to be top-down protocol (Roohinejad and Greiner, 2017). The functionality of food material for the required purpose is a surface area with better properties. Top-down and bottom-up approaches are exhibited in Figure 2 and dependent upon size reduction as finer size material possesses bigger. The top-down protocol is associated with nanotechnology-based devices are monitored with external power to yield the preferred parameters and specific initiation from larger dimensions having stuff with cutting to obtain the desired size (Sangeetha et al., 2017). Using the bottom-up protocol, atoms are converted into nanoscale materials or fixed self-assemblies using complex processes. Self-assembly depends on matching attractive and repulsive forces between molecule pairs used as building blocks for manufacturing efficient supramolecular assemblies (Sanguansri and Augustin, 2006). For example, self-assemblage or grouping of casein micelle gives rise to the formation of carbohydrate- Examples of self-assembled nanostructures in food include the organization of the casein micelle, the structures formed in protein-polysaccharide liposomes, and aggregates. According to a report, the bottom-up method provides a better opportunity for the synthesis of nanostructures with fewer flaws, enhanced identical chemical arrangement, and improved organization (Pathakoti et al., 2017).

8. APPLICATIONS OF ORGANIC AND INORGANIC NANOMATERIALS

8.1. Magnetic nanoparticles (mNPs): Magnetic nanoparticles are one of the most important inorganic nanomaterials (mNPs). A magnetic core (e.g. magnetite (Fe3O4) or maghemite (g-Fe2O3) is generally present. Other metals, such as cobalt and nickel, are also employed, although their applications are limited due to their toxicity and oxidation vulnerability. Iron is essential in almost all biological tissues, yet it has a low bioavailability. It can be harmful to cells in the form of free iron or when it is not coupled with haemoglobin in some situations.

8.2. MRI: MRI is a powerful imaging method that offers the advantage of high spatial resolution of contrast differences between tissues due to its noninvasive nature and capabilities of giving high 3-D resolution and tomographic. Due to their strong magnetic moment, mNPbased contrast agents provide superior image enhancement as well as improved cellular uptake and slower clearance from the target site as compared to typical gadolinium chelates. The use of iron oxide mNPs as MRI signal enhancers has been approved by the US Food and Drug Administration.

8.3. Hyperthermia: Temperature-sensitive cells have a higher rate of tumour cell proliferation than other healthy cells. Intracellular hyperthermia is a strategy for treating malignancies that has been developed using mNPs (specifically SPIOs). This treatment comprises of a delivery agent that functions as a nanoscale heater, causing the cell to heat up and necrosis to occur.

8.4. Magnetic transfection: When nucleic acid delivery is controlled by a magnetic field acting on nucleic acid vectors attached to mNPs, the term “magnetic transfection” is employed. Both ‘big’ nucleic acids and tiny constructs can be transfected via magnetic transfection. These mNPs are designed to bind negatively charged DNAs to the mNPs via electrostatic interactions, with the DNAs being released after cell internalisation. Gold and silver nanoparticles Because of its versatility as an indicator and detection probe, colloidal gold or gold nanoparticles (AuNPs) may be easily manufactured for use in a variety of applications. While most of the attractive qualities of AuNPs in terms of bioapplications are shared with other NPs (e.g. size, inertness, ease of synthesis, and biocompatibility), AuNPs are particularly attractive candidates for biological imaging techniques because they can be visualised based on the interaction of the NPs and light, in which the particles strongly absorb and scatter visible light.

8.5. Biological imaging: For decades, AuNPs have been used as a contrast agent in electron microscopy. Colloidal gold particles are electron dense due to the high atomic number of gold, making them ideal for electron microscopy. AuNPs, on the other hand, have been used in a number of other imaging techniques that rely on the plasmon band.

8.6. Cell delivery vehicles: Most delivery tactics for magnetic and other forms of NPs are relatively similar, such as utilising cancer-targeting moieties conjugated to NPs for transport into cancer tissue. For many years, gold has been utilised to carry chemicals into cells. AuNPs are used in delivery applications because of their tiny size, colloidal stability, ease of synthesis and conjugation, and biocompatibility. Gene guns, for example, can be used to force the introduction of genes into cells, or cellular absorption can be achieved.

8.7. Biosensor: While the methods used in imaging and distribution are mostly passive, AuNPs play a more active role in plasmon-related sensing. In essence, the NPs must be able to detect the presence of analyte molecules and produce a concentration reading. Changes in the optical characteristics of AuNPs are commonly used to accomplish this. The plasmon resonance frequency, which can be exploited for sensing, is a very dependable intrinsic property of AuNPs. Quantum dots QDs are colloidal nanometer-sized crystals made composed of atoms from the periodic table’s groups II to VI (e.g. Cd, Zn, Se, Te) or III to V (e.g. In, P, As). The most common QDs used in bioapplications were made of CdSe and wrapped in a ZnS shell to protect them from the highly poisonous cadmium. The energy bandgap of absorption spectra can be altered from ultraviolet to near-infrared (NIR) region by trapping electrons in various sizes.

8.8. Biological imaging: QDs appeared to be a very attractive probe for longer-term investigations in living cells due to their great photostability and low cytotoxicity, if a few limitations were addressed. Water solubility is a crucial need for in vitro and in vivo imaging at first. Generally, thiol groups (SH) are linked to the ZnS shell with a terminal carboxyl (COOH) to boost the hydrophilicity of QDs, which leads to cell internalisation.

8.9. Single-cell imaging: Single-cell tracking was first developed to explore membrane receptor dynamics. The earliest experiments used micrometer-sized AuNP beads to study transmembrane protein diffusion. Similar experiments employing QDs to target membrane proteins and analyse the mobility and kinetics of receptors, transmembrane proteins, and synapses have recently been published.

8.10. In vivo imaging: The first QD-peptide conjugates to target tumour vasculature in mice were employed in vivo. The tissue-specific peptide coating on (CdSe) Frontiers of Nanoscience ZnS QDs boosted NP accumulation at vascular locations after intravascular injection, according to histology. This study highlighted the potential of employing QDs for molecular-level detection, albeit it does not address QD imaging in a living animal.

8.11. Targeted therapies: QDs are used as delivery and reporter systems in the same way as mNPs are used in transfection therapy in vivo. When compared to other types of delivery vehicles, NP transfection has the advantage of being able to be functionalized with a variety of oligonucleotides and cell-binding ligands at the same time, potentially allowing multiple gene knockdowns and higher affinity for the target cell at the same time. One siRNA per particle in combination with >15 peptides, or two siRNA per particle in combination with 10 peptides, provided excellent knockdown and targeting, according to studies.

8.12. Carbon nanotubes: Hollow and porous NPs, such as nanotubes, nanoshells, and hollow spheres, can hold a lot of cargo, which improves signal and sensitivity. Carbon nanotubes are graphene sheets that are cylindrical in shape. Although most carbon nanotube applications have been focused on microelectronic devices, because to their unique electronic and physical properties, carbon nanotubes have shown some promising properties for biological applications, such as facile translocation through cell membranes and low toxicity.

8.13. Neuronal tissue engineering: CNTs are quickly gaining traction as a technology platform for building new neuroimplantable devices. They have a unique combination of strength and flexibility, as well as physical and chemical qualities that enable them to efficiently conduct electrical current in electrochemical interfaces. CNTs can thus be used in tissue engineering scaffolds in the form of fibres or tubes with sizes similar to those found in neural processes like axons and dendrites. MWCNTs were used to generate rat brain neurons in the application of nanotubes in neuroscience research.

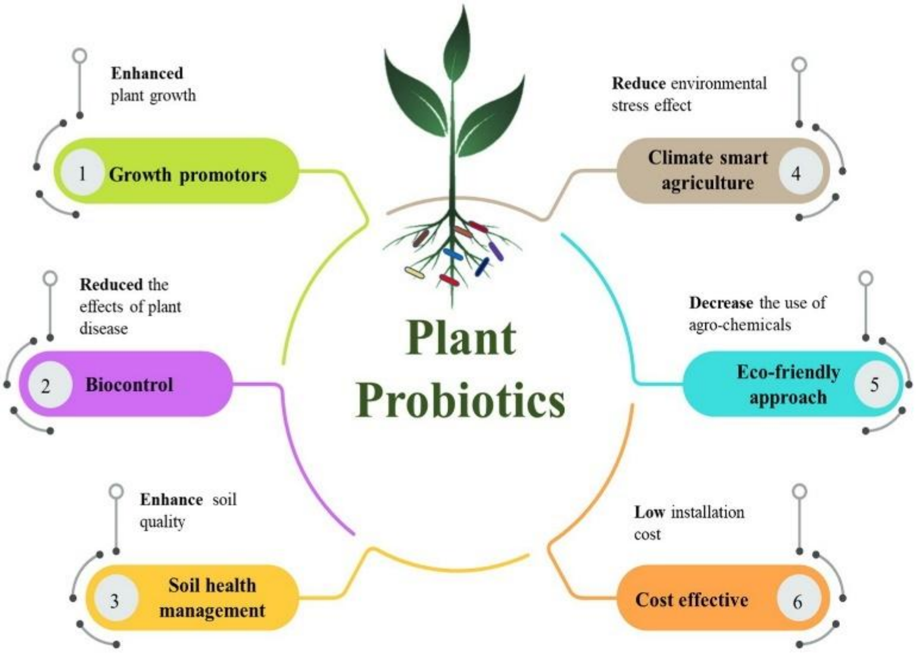
8.14. Imaging and cancer treatment: SWCNTs have been used in the thermal necrosis of cancer cells in the same way that mNPs and AuNPs have. In xenografted mice, intratumoural injection of tubes combined with NIR irradiation resulted in thermal death of human epidermoid oral carcinoma KB tumour cells with minimal side effects up to 6 months after treatment, with elimination via urine in three months.

9. THE ROLE OF NANO-TECHNOLOGY IN ACHIEVING FOOD SECURITY:

The world is exposed to innumerable and unprecedented challenges due to increasing climate change, land constraints, increasing population, industrialization, low productivity, and high postharvest losses (Ndlovu et al., 2020; Gothandam et al., 2018). This has led to food insecurity worldwide. About 2 billion people in the world experience moderate or severe food insecurity (FAO, 2019). The lack of regular access to food puts them at greater risk of malnutrition and poor health. This vastly different world calls for new ways of thinking about food insecurity and its consequences (FAO, 2019). In order to achieve the required food at the global level, various methods and techniques have been put forth by researchers from around the world for boosting crop production, postharvest reduction, and ensuring sustainability (Sivarethinamohan and Sujatha, 2021). Ensuring a safe food supply to protect the health and wellbeing of people worldwide needs advanced technology. Recent research has shown the potential of nanotechnology in improving the agriculture sector by enhancing the efficiency of agricultural inputs and providing solutions to agricultural problems for improving food productivity and security (Singh et al., 2021). The role of nanotechnology in agriculture, postharvest loss reduction, and food processing towards achieving food security was discussed below.

10. AGRICULTURE PRACTICED FOR FOOD PRODUCTION:

Agriculture is practiced for food production via the cultivation of varied crops and raising of livestock. It is considered the backbone economy for most developing countries as a vital role in progress and development. The rising population in the world results in high demand for more food supply, and scientists and engineers are now practicing new methods to increase agricultural production (Baruah and Dutta, 2009). For the last several years, agriculture nanotechnology has focused on research and application to resolve agriculture and environmental issues sustainability, crop improvement, and enhanced productivity. Agricultural nanotechnology seems to be highly interesting for developing countries, regarding the decrease in hunger, underfeeding, and mortality rate in children (Gogos et al., 2012). Developed and emerging countries like Germany, the United States of America (USA), Brazil, China, India, France, and Korea show increased curiosity for using nanomaterials for agriculture uses as revealed via a more producing high number of publications and patents (Gogos et al., 2012).



Sourses: Upadhayay VK, et al., 2023)

Figure 6: Schematic flow chart representing the prolific attributes of using plant probiotics (PPs).

As a potential device, nanotechnology can be applied to renovate agricultural divisions; it helps in learning the biochemical pathways of crops via modifying the conservative methods for evaluating environmental issues and its application to production improvements (Prasad et al., 2017b). Comparisons of nanotechnology with environmentally friendly technologies and agricultural biotechnology show an opportunity for enhanced and quicker influence upon all constituents of the agricultural-value linkage for synchronized public benefits, legal, moral, and environmental effects (Sastry et al., 2011). The prospective use of nanoscale agrochemicals such as nanofertilizers, nanopesticides, nanosensors, and nanoformulations in agriculture has transformed traditional agro-practices, making them more sustainable and efficient (Figure 3). Multiple applications of nanotechnology exist in agriculture including wastewater treatment, reducing the quality of polluted soil, enhance the productivity of crops via security in terms of sensors to detect pathogens (Singh et al., 2021; Axelos and Van De Voorde, 2017). For instance, nanobiosensors is the wide ranging nanotools, scaffold the growth of high-tech agricultural farms and also stand proof for the practical and proposed applications of the nanotools in terms of agricultural inputs control and their management precision (Sivarethinamohan and Sujatha, 2021; Duhan et al., 2017). The application of nanopore bearing zeolite for slow discharge and improved efficacy of enrichers, nanosensors for measuring soil quality and smooth supply mechanisms for herbicides are among positive impact of nanotechnology in agriculture (Chinnamuthu and Boopathi, 2009). Several nanoparticles used for monitoring plant diseases are nano-forms of carbon, silica, silver, and alumino-silicates. The use of nanomaterials for agriculture is proposed to reduce spraying chemicals via the smooth supply of energetic compounds. It can minimize nutrient wastage during applying fertilizer and promote the harvests by enhancing the water and ingredient management (Gogos et al., 2012). The responses of different rice cultivars exposed to engineered nanoparticles at different growth stages and under different conditions were also reported (Wang et al., 2021).

11. NANO-TECHNOLOGY TO CONTROL PLANT DISEASES

About 20–40% of crops are lost due to plant pests and pathogens each year worldwide (Flood, 2010). In modern farming practices, pest management relies heavily on the application of pesticides, such as insecticides, fungicides, and herbicides. The development of cost-efficient, high-performing pesticides that are less harmful to the environment is crucial. The new concepts such as nanotechnology can offer advantages to pesticides, like reducing toxicity, improving the shelf-life, and increasing the solubility of poorly water-soluble pesticides, all of which could have positive environmental impacts (Mali et al., 2020; Worrall et al., 2018). The significance of agricultural nanotechnology, mainly for controlling diseases and safety has been reported elsewhere (Gogos et al., 2012; Rehmanullah et al., 2020; Sastry et al., 2010). Nano-based conventional herbicides and pesticides assist in the slow and continued supply of nutrients and agricultural chemicals in a controlled amount to the plants (Duhan et al., 2017). Nanoparticles may have also a key role in the control of insect pests and host pathogens (Khota et al., 2012). Type of polysaccharides such as chitosan, alginates, starch, and polyesters have been considered for the synthesis of nano-insecticides (Mali et al., 2020). In general, the use of nanoparticles to protect plants can occur via two different mechanisms: (a) nanoparticles themselves providing crop protection, or (b) nanoparticles as carriers for existing pesticides and can be applied by spray (Worrall et al., 2018). However, the use of nanomaterials in plant protection and production of food is under-explored (Prasad et al., 2017a).

12. NANO-TECHNOLOGY TO IMPROVE QUALITY OF SOIL AND FERTILIZER DISTRIBUTION

Nanotechnology for the management of crops is used as an essential technology for enhancing crop productivity. Nanomaterials and nanostructures, such as carbon nanotubes, nanofibers, and quantum dots are now exploited in agriculture research as biosensors for evaluating the quality of soil and fertilizer distribution. The purpose of nanoparticles is to minimize the spread of chemicals amount, reduce the nutrient loss during fertilization, and increase the quality and yield with proper nutrient (Sangeetha et al., 2021). The development and use of vermiculite, nanoclay, and zeolite could improve fertilizer efficacy and crop production for ecological agriculture in coarse-textured (Sivarethinamohan and Sujatha, 2021). Amending sandy loam soils with inorganic amendments reduce NH_4–N passage and increasing the yield of N fertilizer in ecological agriculture systems (Mazloomi and Jalali, 2019). Nanoclay is systematized into a number of modules such as montmorillonite, bentonite, kaolinite, hectorite, and halloysite on the basis of chemical composition and nanoparticle morphology (Sivarethinamohan and Sujatha, 2021).

Most of the productivity of agricultural practices is heavily dependent on fertilizer use. Studies show that crop production is linearly determined by exhaustive application of fertilizers to increase soil fertility (Rehmanullah et al., 2020). The use of nano fertilizer is crucial to enhance crop production. Nano fertilizer is a material with nanometer-size which improves the delivery to plants and managed the slow release of nutrients into the soil gradually in a highly controlled way, hence stopping eutrophication and contamination of water (Davari et al., 2017). Nanotechnology makes the exploitation of nanostructured or nanomaterials for fertilizer transport or limited release routes to construct smooth fertilizer as new opportunities to modify nutrient usage efficacy and reduce charges for environmental safety (Hai-Xin et al., 2011). Nano-fertilizer could improve nutrient efficiency through encapsulation within nanoparticles which is conducted by three methods. (a) Nutrient encapsulation within nanoporous structures, (b) Coating of thin polymeric film, or (c) Delivery in the form of particle or suspensions with nanoscale sizes (Davari et al., 2017; Rai et al., 2012). Nanoscale fertilizers could lead to the more effective delivery of nutrients as their small size may allow them access to plant surfaces and transport channels (Mastronardi et al., 2015). Nano-fertilizer extracted and prepared from banana peels were used in the growth of tomatoes, peppers, or flowers (Sivarethinamohan and Sujatha, 2021). Nano fertilizers were used for the growth and improvement of different crops, for instance, nanoparticles of ZnO for chickpea, silicon dioxide and iron slag powder for maize, colloidal silica and NPK for tomato, TiO_2 for spinach, gold and sulfur fertilizers were used for the growth of grapes (Sivarethinamohan and Sujatha, 2021). Fertilizer usage with nanoscale transporters may be subjected in a way so that they anchor the roots of the plant with the surrounding soil contents and organic material hence decreasing chemical loss and lessening environmental issues (Dasgupta et al., 2015). Nanoscale fertilizers can decrease the toxicity of soil and hence the potential undesirable impacts accompanied by high dosage are reduced (Davari et al., 2017). Such nano fertilizers slow down the nutrients release and extend the duration of fertilizer impact (Naderi and Danesh-Shahraki, 2013). TiO_2 nanoparticles have shown a major effect on the growth of maize crop; moreover, SiO_2 plus TiO_2 nanoparticles elevated the action of nitrate and increased plant absorption potential, by controlled use of water and fertilizer with the efficient outcome (Abobatta, 2018; Sekhon, 2014).

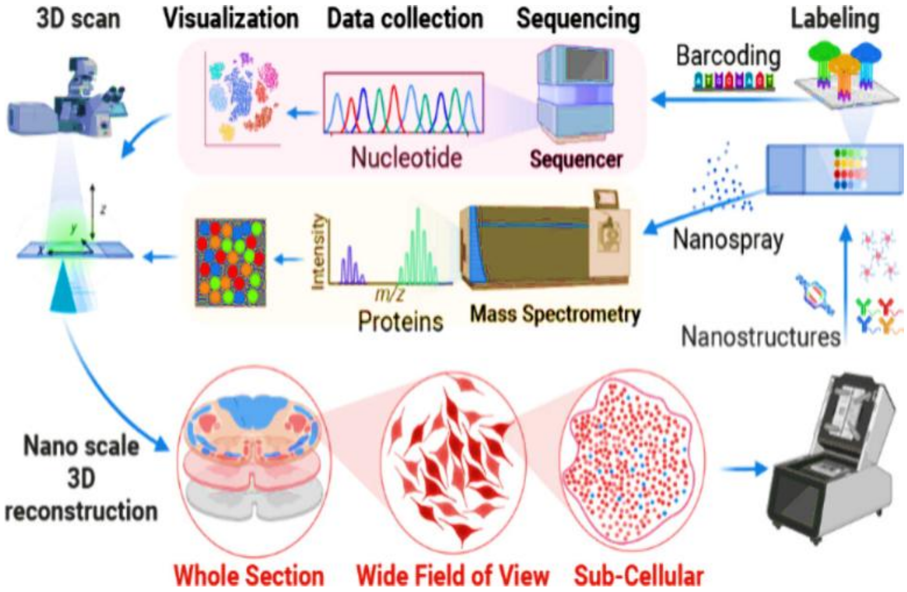
13. NANO-TECHNOLOGY AND GENE SEQUENCING

The use of nanotechnology also facilitated gene sequencing that contributed to the improved identification and use of plant trait means, modifying their potential to respond against environmental pressures and ailments. Quantum dots and nanoparticles have proved to a biological marker associated with outstanding accuracy (Sharon et al., 2010). Optical mapping of DNA in the age of nanotechnology and nanoscopy also reported (Levy-Sakin and Ebenstein, 2013). Optical mapping of DNA grants accesses to genetic and epigenetic information on individual DNA molecules. Nanopore sequencing could allow sequencing of single DNA molecules spanning tens of kbp (perhaps up to 100 kbp) thus lifting the limitations of short-read data (Levy-Sakin and Ebenstein, 2013). In general, nanotechnologies have been applied in a variety of contexts, including genome sequencing, targeted resequencing and discovery of transcription factor binding sites, noncoding RNA expression profiling, and molecular diagnostics (Elingarami et al., 2013).

13.1. Nanotechnology in Genetic Engineering

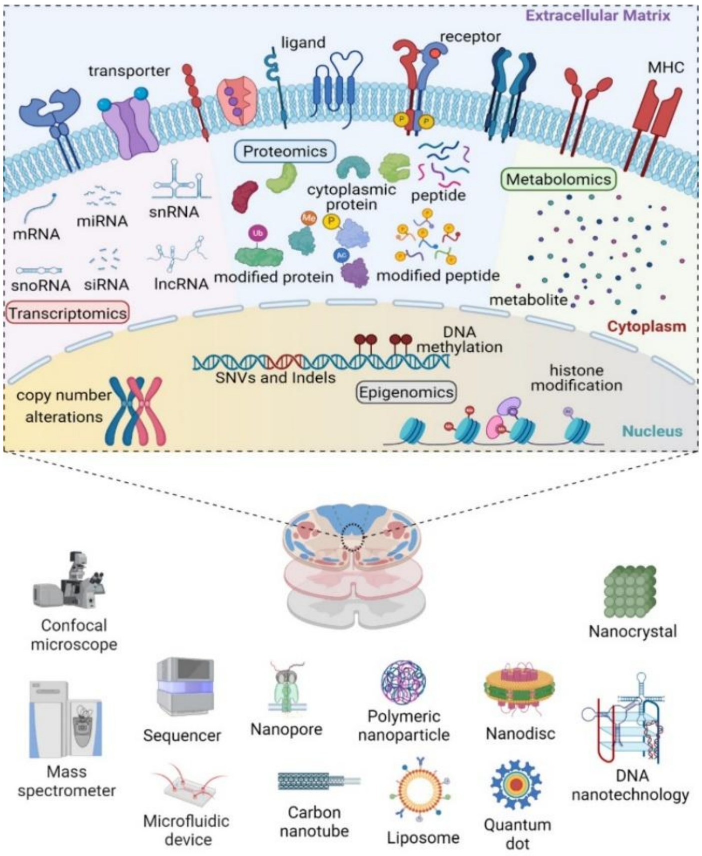
Gene editing techniques allow precise modifications of plant and animal genes, revolutionizing biomedical sciences. These techniques primarily involve introducing transgenes or CRISPR into plants or animals using specific gene delivery systems. However, traditional delivery systems are time-consuming, involve complicated protocols, and can damage tissues. In contrast, nanotechnology-based gene delivery offers high efficiency for temporal (transient) and permanent (stable) gene modifications across various species (Ahmar, S., *et al*. (2021)

Carbon-based nanoparticles, such as fullerenes and carbon nanotubes, exhibit excellent physical and chemical properties, including high aspect ratio, tensile strength, surface area-to-volume ratio, biocompatibility, and biostability, making them efficient gene carriers. For example, single-walled carbon nanotubes complexed with chitosan can transfer DNA into chloroplasts of mature plants (Begum, R., Jayawardana, NU. (2021).



Sourses: Ruixuan Wang et al.,2024

Figure 7: Nanotechnology facilitated gene sequencing that contributed to the improved identification and use of plant.



Sourses: Ruixuan Wang et al.,2024

Figure 8: Spatial omics provide information about transcriptomics, proteomics, metabolomics, and epigenomics while preserving spatial information, such as subcellular localization. Examples of nanotechnology for biological applications are shown. Abbreviations: mRNA: mRNA; miRNA: microRNA; snRNA: small nuclear RNA; snoRNA: small nucleolar RNA; siRNA: small interfering RNA; lncRNA: long noncoding RNA; SNV: Single-Nucleotide Polymorphism; MHC: Major Histocompatibility Complex. The figure was created with BioRender.

Mesoporous silica nanoparticles (MSNPs) with honeycomb structures are widely used in gene editing for plant and animal cells. They prevent molecule leaching by entrapping them inside pores and encapsulating them. Due to their safety, biodegradability, and biocompatibility, MSNPs effectively deliver genetic materials of various sizes, shapes, and functionalities, including proteins, DNA, and ribonucleic acid (Begum, R., Jayawardana, NU. (2021).

Metallic nanoparticles (MNPs), composed of elements like gold, silver, iron oxide, copper oxide, and zinc oxide, readily attract negatively charged DNA molecules due to their positive surface charge. They can deliver DNA into vegetative and reproductive tissues of plants to enhance their functions. For instance, MNP-transfected pollen grains in transgenic cotton plants exhibit resistance against insects (Begum, R., Jayawardana, NU. (2021).

Quantum dots, another type of metal-based nanoparticle, have successful applications in gene engineering. For example, ZnS-based plasmid DNA introduced into young tobacco plants effectively integrates the gene of interest into the tobacco genome with stable expression.

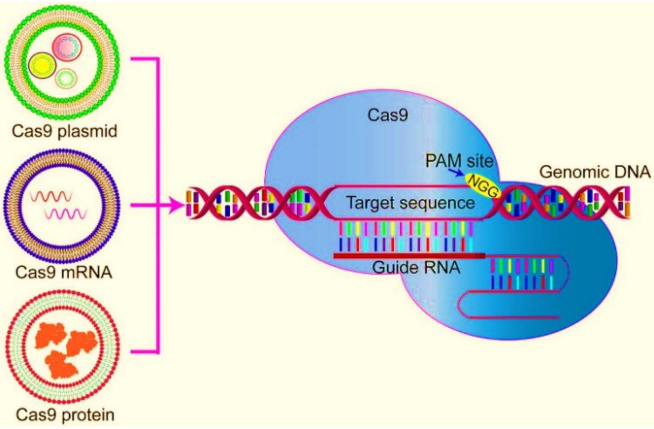
In addition, nanoparticles based on organic polymers, lipids, peptides, and vesicles also function as bioactive carriers in gene delivery and editing (Begum, R., Jayawardana, NU. (2021). Polymeric nanoparticles allow the combined application of gene therapy and anticancer drugs or nano agents for photothermal therapy, enhancing targeted delivery and therapeutic potency (Ghani, MW., Iqbal, A., Ghani, H., Bibi, S., Wang, Z., Pei, R. (2023).

Nanoparticle-assisted delivery of CRISPR/Cas systems for *in vivo* genome has been proposed for the liver, where nanoparticles accumulate after systemic administration. Additionally, lipid nanoparticles have shown high success rates in selectively delivering CRISPR payloads to the liver, spleen, lungs, and tumor tissues.

13.2. Advantages of Nanotechnology in Gene Manipulation

Conventional gene editing approaches face challenges such as limited host range, low transformation efficiency, tissue damage, and random integration of DNA into the host genome. Additionally, traditional chemical and physical biotransformation methods often involve excessive chemicals and energy (Begum, R., Jayawardana, NU. (2021). In contrast, nanocomposites offer promising advantages for CRISPR/Cas delivery due to their excellent biocompatibility, lower toxicity, and enhanced delivery efficacy (Ghani, MW., Iqbal, A., Ghani, H., Bibi, S., Wang, Z., Pei, R. (2023).

The successful expression of exogenous genes requires stable integration to develop transgenic plants. Nanoparticles help maintain the stability of the genes of interest due to their small size and surface effects (Begum, R., Jayawardana, NU. (2021). The tunable physicochemical properties of nanocomposites also allow easy conjugation with various functional materials (Ghani, MW., Iqbal, A., Ghani, H., Bibi, S., Wang, Z., Pei, R. (2023).



Sourses: Duan L, Ouyang K, et al.,2024

Figure 8: Representative genome editing by three forms of clustered regularly interspaced short palindromic repeat (CRISPR)/Cas9. Cas9 plasmid DNA, RNA, or protein delivery *via* nanoparticles to be used for precise genome editing. Sourses: Duan L, Ouyang K, Xu X, Xu L, Wen C, Zhou X, Qin Z, Xu Z, Sun W and Liang Y (2021) Nanoparticle Delivery of CRISPR/Cas9 for Genome Editing. *Front. Genet.* 12:673286. doi: 10.3389/fgene.2021.673286

Nanoparticles can be charged, and their surfaces modified to bind with diverse biomolecules. Engineered nanoparticles enable cargo delivery to subcellular parts, such as mitochondrial or chloroplast DNA, without the species- and tissue-specific limitations of conventional biomolecule delivery methods. For example, nanoparticles can traverse plant cell walls due to their small size.[3] Additionally, nanocomposites allow organ-specific delivery of CRISPR/Cas systems (Ghani, MW., Iqbal, A., Ghani, H., Bibi, S., Wang, Z., Pei, R. (2023).[2]

13.3. Nanotechnology in Gene Manipulation: Challenges and Limitations

Despite the revolutionary potential of nanotechnology in gene editing, its large-scale adoption faces several challenges. Primarily, nano-phytotoxicity can negatively impact plants' physical and reproductive growth. Nanomaterials released into the environment can damage plants and ecosystems, and blockages in a plant's vascular system due to nanomaterials can structurally damage DNA and induce oxidative stress (Ahmar, S., *et al*. (2021).

The delivery of CRISPR/Cas tools through nanocomposites has not yet been tested on human tissue-derived organoids, which provide better preclinical modeling by mimicking patients' genetic setups.[2] Additionally, nanoparticle-based gene modification has been studied only in a few plants, such as cotton, tobacco, tomato, wheat, lupin, pumpkin, maize, and potato, with limited studies on monocotyledons (Begum, R., Jayawardana, NU. (2021).

Different nanomaterials behave differently in specific plant cells, requiring thorough dose optimization and spectral tuning for various species. The biomolecule-binding affinity of nanoparticles varies with their structure, charge, chemical composition, and surface area. Thus, it is crucial to ensure that nanoparticles do not interfere with cellular processes to avoid disrupting cell structural stability and metabolic pathways (Ahmar, S., *et al*. (2021).

13.4. Future Directions in Nanotechnology for Gene Manipulation

Nanotechnology's transformative potential in gene manipulation is being explored for novel applications. Nanorobots, controlled devices made up of nanometric components, can interact with and diffuse through cellular membranes. This direct access to the cellular level improves cancer treatment efficiency through novel methods like gene therapy, including gene correction, silencing, activation, and editing Chattha, GM., *et al*. (2023). Overall, nanostructures and nanocomposites hold promise for accelerating the clinical application of gene modification methods, such as CRISPR delivery systems, potentially revolutionizing healthcare (Ghani, MW., Iqbal, A., Ghani, H., Bibi, S., Wang, Z., Pei, R. (2023). They also offer significant advantages in designing smart crop systems, making agriculture more effective, robust, and sustainable in the face of the impending climate crisis. The existing challenges in nanotechnology-based gene engineering can be addressed by integrating different gene delivery methods, like magnetofection and CRISPR, and fabricating novel hybrid nanomaterials. Ahmar, S., *et al*. (2021).

14. POSTHARVEST LOSS OF REDUCTION

In developed countries, greater than 40% losses of food (cereals, roots and tubers, pulses and oil crops, vegetables and fruit, fish meat, and dairy) occurs at trade and customer stages, while in the case of developing countries, greater than 40% losses of food occur at post-harvest stage and processing point (FAO, 2019; Gustavsson et al., 2011). Newly harvested high moisture unpreserved yields may quickly deteriorate owing to microorganism's attack. Newer and advanced technologies such as nanotechnology can help for decreasing post-harvest losses. Nanotechnology application can minimize post-harvest losses by designing functional packing ingredients with the least quantities of bioactive constituents, improved gas and mechanical properties with a reduced effect on sensor qualities of vegetables and fruits (Flores-López et al., 2016).

Edible coatings are used as a liquid on food, generally by dipping the product in a solution-providing substance made by the structural medium (carbohydrate, lipid, protein, or mixture). They protect untreated foods from worsening via hindering dehydration, overturning respiration, refining textural features, aiding to preserve volatile aroma compounds, and decreasing the growth of microbes. Nano-coatings with edible quality deposited on different foodstuff provides a fence to gas and moisture exchange and delivering flavors, colors, enzymes, antioxidants, and browning resistant agents that may enhance the shelf life of synthetic foods (Zambrano-Zaragoza et al., 2018). The technology enables the formation of nanoscale coatings up to five nano meter thickness (Sekhon, 2010). The use of edible coatings and thin films are common for horticultural commodities. The use depends on properties like cost, availability, functional qualities, mechanical properties (elasticity, tension), photosensitive properties (brilliance and opacity), the fencing effect versus gas flow, structural hindrance to water migration, microbes and sensory suitability (Zambrano-Zaragoza et al., 2018; Falguera et al., 2011).

Various nanoscale edible coatings are applied to food to control the post-harvest excellence of new harvested products. Silver nanoparticles are of increasing attention recently owing to their antimicrobial properties essential for processing food. The use of PVP-based silver nanoparticles on asparagus, considerably delayed the growth of microbes, slowing the loss of weight and decreased changes in skin color (An et al., 2008). In another report, gelatin-derived edible coatings with cellulose nanocrystal considerably improved the shelf life of strawberries (Fakhouri et al., 2014). Chitosan-assisted nano-silica coating beneficially improved the physicochemical and physiological value regarding longan fruit within ambient temperature as compared to other treatments via proficiently providing an outstanding semi-permeable film (Shi et al., 2013). Moreover, chitosan film-based nano-SiO_2 (Yu et al., 2012) and alginate or lysozyme-based nanolaminate coatings (Medeiros et al., 2014) investigated to reserve the value of fresh diets during prolonged storage. Nano-ZnO coating also reduced the microbial damage and kept the post-harvest value of some fruits during storing (Sogvar et al., 2016).

Nanotechnology can also be applied in grain quality control using nanosensors (Bouwmeester et al., 2009). The sensors are capable to respond to changes in the environment during storage (temperature, oxygen exposure, and relative humidity), degradation products, or contamination by microbes. They are also applied to respond to the presence of fungus or insects in the stored grain (Axelos and Van De Voorde, 2017). Nanosensors for grain quality observing have also been developed by using polymer nanoparticles that respond to volatile agents and other analytes in an environment of stored foods and hence detect the cause and the kind of decomposition involved (Neethirajan and Jayas, 2011).

14.1. Food processing

Globally, biggest food companies searching for various methods to modify the competence, safety, value, and nutritional properties of food. Newer technologies are required for food industries to enhance productivity, market price, and quality. Plentiful uses of nanotechnology regarding food production and processing are developed including nano-based-food additives, nanoencapsulation, nanosensors, nanoparticles-based smart distribution systems, nano-packing, plus medicines, and health care (Rashidi and Khosravi-Darani, 2011). Its applications are also for encapsulation formation, biopolymer matrices, emulsions, simple solutions, and associated colloids offer effective delivery systems. Industrial food processing by nanotechnology is gaining momentum particularly, for flavor encapsulation or odor enhancement, modification of food texture or value improvement, newer gelation or viscosity increasing agents (Duncan, 2011). Food nanotechnology emphasizes the synthesis of nanometer-scale structures with exclusive properties be used for different purposes, such as delivery arrangements, food interaction surfaces having exclusive superficial properties, devices for food characterization, microfluidic instruments, sensor technology, and nanocomposite coatings, among numerous other uses (Sadeghi et al., 2017).

Formation of nanoemulsions takes place by minute emulsion droplets at the nanoscale (oil/water system) showing sizes <100 nm (Anton and Vandamme, 2011). They need higher mechanical energy like a high-pressure homogenizing step or using a microfluidizer or sonication protocol to form the distributed phases. Nanoemulsions minimize the requirement for stabilizers, owing to their protection against food breaking and split-up hence considerably decrease the amount of fat required (Dasgupta et al., 2015). Several nanoemulsions seem optically clear and possess many technical advantages for mixing into drinks (Prasad et al., 2017a). The final possessing products of nanoemulsions are very creamy like usual food products, having no changes felt to mouth and taste (Dasgupta et al., 2015). Nanoemulsions are applied to modify food for salad dressing, the flavor in oils, sweeteners, improved beverages, and other food processing.

14.2. Nanotubes in food and agriculture

Nanotubes are Buckyballs having two sides decorated with other atomic groups incorporated in the typical hexagonal shape to give a hollow carbon tube. Nanotubes withstand high temperature, having a flexible and strong nature which is applied for use in medical tools, alumina, sports apparatus, and equipment for food processing (Rashidi and Khosravi-Darani, 2011). Nanotubular textures are made from several varied materials like inorganics, carbon, bio-microtubules, viral proteins, amyloid proteins, porins, lactalbumin, DNA28, carbohydrates, lipids, synthetic polymers, plus other organics (Scanlon and Aggeli, 2008).

Carbon nanotubes induce improved mechanical properties in food packaging (Abdelmonem, 2020). Carbon nanotubes and polyamides have employed to increase the tensile strength of some polymers (Kim et al., 2008). Carbon nanotube-based biosensors have been practiced in detecting microbes, toxic elements, and other metabolites in beverages and food owing to their faster detection, simple protocol, and cheaper cost (Singh et al., 2017). TiO_2 based carbon nanotubes have been witnessed to increase disinfectant potential against spores of Bacillus cereus (Krishna et al., 2005). Silver deposited TiO_2 nanoparticles increased their bacterial killing effects Vs E. coli (Kim et al., 2006). Strong antimicrobial impacts of carbon nanotubes made them killed via direct contact (Abdelmonem, 2020).

Nanotubes have also linked with modern agricultural activity. According to some reports, various nanoparticles can enter the cell walls of plants. It was known that carbon nanotubes can enter tomato seeds to affect their sprouting and development (Khodakovskaya et al., 2009). Figure 7 illustrates the germination of the development of tomato treated with various concentrations of carbon nanotubes (0, 10, and 40 µg/L) showing a wonderful growth in biomass. This is due to increased uptake of water by carbon nanotubes resulting in the improvement of the plant. Gold-derived mesoporous silica nanoparticles also entered through the cell wall and helped in the penetration of DNA into the cell (Torney et al., 2007).

14.3. Nano sensors in food and agriculture

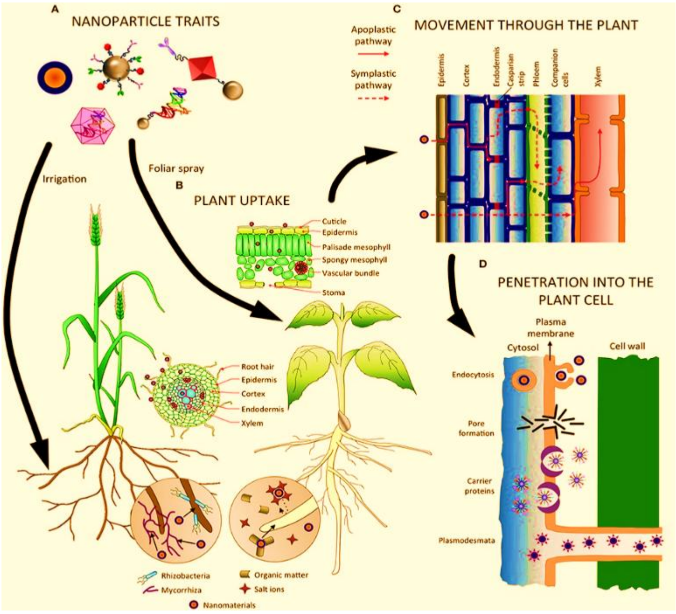
The use of biosensors combined with improved technologies in the field of molecular biology, nanomaterials, and microfluidics have enormous applications for the productivity of crops. These are also applied to monitor the activity of microorganisms in the soil and able to predict the likely incidence of soil infections. The basic principle related to soil examination with the biosensor is to find out the comparative action of positive and negative microorganisms in soil depends upon variation on oxygen usage during their breathing. They also offer many opportunities in sensing contaminants and their hindrance, via using new properties related to nanomaterials (Baruah and Dutta, 2009). Biosensors for detection of the nitrate concentration in plants as well as detection for markers to identify infected plants are reported for methyl salicylate and azelaic acid (Griesche and Baeumner, 2020). The use of biosensors for monitoring of Penicillium digitatum infection in citrus fruit was reported (Chalupowicz et al., 2020). Smart delivery systems and nanosensors are applied to help in efficient natural agricultural means like nutrients, water, and chemicals using precision farming for example satellite monitoring, geographic systems, and distant detecting tools that remotely can detect pests on crops or indication of strain like drought (Sekhon, 2014). The application of independent sensors connected to GPS monitoring in real-time is thought to play a key role in nanotechnology-assisted tools (Davari et al., 2017). Arrangement of nanosensors can be carried out throughout the field for monitoring crop growth and soil parameters.

14.4. The challenges of nanotechnology in food and agriculture system

Nanotechnology tremendously used for food and agricultural benefits as reviewed earlier. However, nanomaterials are associated with many safety issues due to their potential risk values penetrating the cells owing to their minute sizes and could exist in the system (De Azeredo, 2009; Sharma et al., 2017). Enhanced application of nanotechnology in agricultural practices and food products are of tremendous concern amongst big sector of the society because of several antagonistic effects of different nanoparticles (Baruah and Dutta, 2009). Although properties and protection of the substances in bulk are generally evident, nanoscale complements repeatedly demonstrate varied properties as compared to those at the macroscale (De Azeredo, 2009). The threat associated with nanotechnology is largely due to the small size of nanoparticles with larger surface areas which are easily dispersible, penetrating cells to reach quite distant areas of the body, for causing potential toxicity (Dasgupta et al., 2015). Due to similarity in size with DNA, nanomaterials possess the chance to react with the biological specimens (Baruah and Dutta, 2009).

Degradation of nanocomposites can occur owing to environmental conditions with the release of inserted nanomaterials from polymeric texture into the environment (Moustafa et al., 2019). The strength of some food packaging, like low-density polyethylene, is changed after exposure to environmental effects, ultraviolet rays, or ozone in humid conditions (Han et al., 2018). According to Han et al. (2018), polyethylene samples with low density suffered oxidation under UV light or ozone-producing considerable change in structural, physical, and thermal properties. In the agriculture sector, pesticides and nano fertilizers are used are spread into the water, soil, or atmosphere, resulting in high health threat for farmers (Roohinejad and Greiner, 2017). The accumulation of nanoparticles in the soil is expected to impair plant growth and accumulate into edible tissues (Rajput et al., 2020).

Generally, effective guidelines, policies and regulatory systems are required for the safer utilization of nanoparticles in food industry. For instance, Food and Drug Administration (FDA) involved in the regulation of nanofoods and food packaging in the USA and European Union control the nanotechnology-based food ingredients in Europe (Nile et al., 2020). However, most countries producing nano materials do not have proper nanotechnology specific regulations (Nile et al., 2020). Therefore, complete government guidelines and legislations, as well as rigorous toxicological screening methodologies are essential for the legal nanotechnological applications (Nile et al., 2020). NPs application is important to mitigate the abiotic stress effects of salinity on plants. At the germination stage, the use of Ag NPs in Lathyrus sativus under salt stress improves germination percentage, shoot and root length, and seedling FW and DW; thus, this enhanced osmotic regulation and reduced the negative effects associated with salinity (Hojjat, 2019). Noman et al. (2020) found that applying Cu NPs to the soil reduced oxidative stress in wheat and significantly increased plant development and yield.The use of NPs in wheat not only enhances plant development but also improves germination performance under salt-stress conditions (Shi et al., 2016). Preapplication of Ag NPs to wheat seeds alters antioxidant enzyme activities, reduces oxidative damage, and elevates salt-stress tolerance in such plants (Kashyap et al., 2015). In addition, ZnO NPs are known to increase the DW of sunflowers under salt stress (Torabian et al., 2016). CeO NPs (100 and 200 mg kg–1) was found to enhance the physiological responses of B. napus under salt stress (100 mM NaCl).



Sourses: Alejandro Pérez-de-Luque, 2017

Fig 6: Factors influencing absorption, uptake, transport and penetration of nanoparticles in plants. (A) **Nanoparticle traits affect how they are uptaken and translocated in the plant, as well as the application method.** (B) **In the soil, nanoparticles can interact with microorganisms and compounds, which might facilitate or hamper their absorption. Several tissues (epidermis, endodermis…) and barriers (Casparian strip, cuticle…) must be crossed before reaching the vascular tissues, depending on the entry point (roots or leaves).** (C) **Nanomaterials can follow the apoplastic and/or the symplastic pathways for moving up and down the plant, and radial movement for changing from one pathway to the other.** (D) **Several mechanisms have been proposed for the internalization of nanoparticles inside the cells, such as endocytosis, pore formation, mediated by carrier proteins, and through plasmodesmata**.

15. APPLICATION OF NPS UNDER SALINITY CONDITIONS

CeO NPs are also known to boost plant biomass in salt-stressed canola (Rossi et al., 2016). The application of Ag NPs to basil seeds under salt-stress conditions increases seed germination (Darvishzadeh et al., 2015; Hojjat and Kamyab, 2017). Ag NPs applied to S. hortensis increase plant resistance to salt stress while reducing salt-stress–induced effects on germination percentage and plant shoot length (Nejatzadeh, 2021). Furthermore, the use of Ag NPs in salt-stressed cumin plants substantially improves plant salt resistance (Ekhtiyari and Moraghebi, 2012). Finally, Askary et al. (2017) reported that Fe3O4 NPs protects mint plants from oxidative stress caused by increased NaCl content.

16. MOVEMENT OF NANOPARTICLES INSIDE PLANTS

Once the nanoparticles penetrate into the plant, there are two ways for them to move through tissues: the apoplast and the symplast (Figure 1). Apoplastic transport takes place outside the plasma membrane through the extracellular spaces, cell walls of adjacent cells and xylem vessels (Sattelmacher, 2001), whereas symplastic transport involves movement of water and substances between the cytoplasm of adjacent cells through specialized structures called plasmodesmata (Roberts and Oparka, 2003) and sieve plates. The apoplastic pathway is important for radial movement within plant tissues, and allows nanomaterials to reach the root central cylinder and the vascular tissues, for further movement upwards the aerial part (González-Melendi et al., 2008; Larue et al., 2012; Zhao et al., 2012; Sun et al., 2014). Once inside the central cylinder, nanoparticles can move toward the aerial part though the xylem, following the transpiration stream (Cifuentes et al., 2010; Larue et al., 2012; Wang et al., 2012; Sun et al., 2014). Nevertheless, reaching the xylem through the root implies crossing a barrier to the apoplastic pathway, the Casparian strip, which must be done following a symplastic way (Robards and Robb, 1972) via endodermal cells. Indeed, some nanomaterials can be stopped and accumulated at the Casparian strip (Larue et al., 2012; Sun et al., 2014). Another important symplastic transport is possible too, using the sieve tube elements in the phloem, and allowing distribution toward non-photosynthetic tissues and organs (Wang et al., 2012; Raliya et al., 2016). In the case of foliar applications, nanomaterials must cross the barrier the cuticle presents, following the lipophilic or the hydrophilic pathway (Schönherr, 2002). The lipophilic one involves diffusion through cuticular waxes, whereas the hydrophilic pathway is accomplished through polar aqueous pores presented in the cuticle and/or stomata (Eichert and Goldbach, 2008; Eichert et al., 2008). Because the diameter of cuticular pores has been estimated around 2 nm (Eichert and Goldbach, 2008), the stomatal pathway appears as the most likely route for nanoparticle penetration, with a size exclusion limit above 10 nm (Eichert et al., 2008).

17. INTERACTION OF NANOMATERIALS WITH PLANT CELLS

In order to enter the symplastic pathway, nanomaterials must be internalized by the plant cell and cross the plasma membrane (Figure 1). There are several ways for nanoparticles to achieve this, although such mechanisms are better studied in animal cells and less known in plants (Rico et al., 2011; Schwab et al., 2015):

1. **Endocytosis:** The nanoparticles are incorporated into the cell by invagination of the plasma membrane, originating a vesicle that can travel to different compartments of the cell (Etxeberria et al., 2006).

2. Pore formation: Some nanomaterials can disrupt the plasma membrane, inducing the formation of pores for crossing into the cell (Wong et al., 2016) and reaching directly the cytosol without being encapsulated in any organelle (Serag et al., 2011).

3. **Carrier proteins:** Nanoparticles can bind to surrounding proteins, including cell membrane proteins that could act as carriers for internalization and uptake inside the cell (Nel et al., 2009). Specifically, aquaporins have been suggested as transporters for nanomaterials inside the cell (Rico et al., 2011), but their tiny pore size, ranging between 2.8 and 3.4 Å (Wu and Beitz, 2007), makes them unlikely as channels for nanoparticle penetration (Schwab et al., 2015), unless such pore size could be modified and increased.

4. **Plasmodesmata:** Another way for nanomaterials entering a cell is through plasmodesmata, specialized structures for transport between cells (Roberts and Oparka, 2003). Of course, it involves that the nanomaterials should be already in the symplast, but this mechanism is really important in plants for translocation through the phloem (Zhai et al., 2014).

5. **Ion channels:** They have been proposed as probable pathways for nanoparticles entry into the cell (Rico et al., 2011; Schwab et al., 2015). However, the size of such channels is around 1 nm, which makes very unlikely for nanoparticles

to effectively cross them without important modifications.

How nanoparticles are internalized in the cells is another key question, because it will again influence the practical application of the nanomaterials. If we want to deliver chemicals inside specific cell organelles, then endocytosis appears as the most suitable way. On the contrary, for delivery in the cytosol, pore formation should be the most direct way for it. Additionally, we could be interested in nanomaterials that do not penetrate inside the plant cell but in other organisms, such as bacteria or fungi, in order to treat crop systemic diseases and infections (Rispail et al., 2014).

18. APPLICATION OF NPS UNDER DROUGHT CONDITIONS

Drought is considered a major abiotic stress that can drastically limit crop production (Al-Ashkar et al., 2021; Roy et al., 2021). NPs application is an efficient method for alleviating the impact of drought on plants by increasing antioxidant enzyme activity, improving phytohormone levels, and affecting physiological properties. The use of analcite NPs in soil under hot, dry conditions has been shown to promote germination and plant growth in wheat (Hossain et al., 2021). In addition, the use of ZnO NPs in soybean seeds under arid conditions increases the germination percentage of the seeds (Sedghi et al., 2013). Under drought stress, the use of Cu and Zn NPs in wheat plants increases their antioxidant enzyme activity and relative moisture content, decreases thiobarbituric acid levels, affects reagent precipitation, stabilizes photosynthetic pigment levels in leaves, and reduces the effects of stress (Taran et al., 2017; Semida et al., 2021). In response to drought stress, SiO2 NPs application can increase shoot length and relative water content (RWC) in barley, while reducing superoxide radical formation and membrane damage (Turgeon, 2010).

Under HMs stress conditions, the application of NPs to plants reduces the concentration of HMs in the soil, regulates the expression of HMs transfer genes in plants, increases the activity of plant antioxidant systems, improves physiological functions, and stimulates the production of protective substances such as root secretions, phytochelatin, and organic acids (Rui, 2021). The application of Si NPs on maize plants under arsenic (As) stress reduced the total chlorophyll, carotenoid content, and total protein content; in addition to mitigating the adverse effects of As stress on maximum quantum efficiency, photochemical quenching, and non-photochemical quenching of FS II (Tripathi et al., 2016). Soil application of TiO2 NPs can effectively limit Cd toxicity by enhancing the physiological parameters and photosynthetic rate in soybean plants; therefore, TiO2 NPs are vital to mitigate the effects of HMs-induced oxidative stress (Singh and Lee, 2016). When treated with SiO2 NPs, the activities of enzymes, such as ascorbate peroxidase (APX) and superoxide dismutase (SOD), increased; whereas the effects of oxidative stress were reduced in pea seedlings under Cr stress (Tripathi et al., 2015b). Furthermore, de Sousa et al. (2019) revealed that Si NPs can reduce Al toxicity by activating the antioxidant defense mechanism in maize plants. Konate et al. (2017) found that Fe3O4 NPs protected wheat against Cd-induced oxidative stress. Foliar applications of Se NPs to Chinese cabbage under Cd stress increased the biomass, plant height, leaf chlorophyll content, SOD levels, and plasma glutathione peroxidase (GPX) content, whereas the Cd and malondialdehyde (MDA) contents of the leaves were reduced (Zhang, 2019). Similarly, Si NPs alleviate the effect of Cd stress in rice (Wang et al., 2015). The combined use of foliar ZnO NPs and soil biochar in plants was found to be more effective against Cd stress (Rizwan et al., 2019a). Similarly, the coapplication of Fe NPs and biochar reduced the effects of Cd stress in rice (Hussain et al., 2019c). The use of FeO NPs in Cd-stressed wheat reduced the leaf electrolyte leakage ratio and Cd content in grains, while improving the antioxidant enzyme action and DW of the plants. Foliar application of Fe NPs is preferable over soil usage. Rahmatizadeh et al. (2019) also found that 20 mg L–1 of Fe3O4 NPs reduced Cd accumulation and improved Cd toxicity by increasing nutrient uptake in tomato plants.

19. NANOFERTILIZERS VERSUS COMMERCIAL FERTILIZERS

Agrochemicals can be released in a controlled manner, and macromolecules can be delivered selectively. By incorporating nanoscale transporters and chemicals, the efficient use of fertilizers and pesticides can be improved, resulting in a reduction in the amount used without compromising the yield of crops. In contrast, commercial fertilizers, provide fewer benefits to plants because of their larger particle size and reduced solubility. In addition, repeated chemical fertilizer application result in a toxic build-up of HMs that disrupts the ecological balance in the soil. In addition, excessive application of chemical fertilizer can contribute to soil pollution due to leaching or being not fully utilized by plants; thus, the remaining is converted into insoluble salts in the soil.

Nanoagrochemicals play an important role in enhancing nutrient use efficiency and water quality management for sustainable agriculture. However, bioaccumulation and long-term exposure of NPs to plants may have a negative impact on edible plants and food chains (Rajput et al., 2020). According to Staroń et al. (2020), NPs can be taken up and deposited in the edible tissues of crop plants. The accumulation of NPs or metal ions in their natural state can disrupt plant physiological activities; affect the integrity of cellular and sub-cellular organelle organizations; and modify the content of proteins, lipids, and nucleic acids by creating hydroxyl radicals (Cota-Ruiz et al., 2018; Rajput et al., 2020). Overall, the wide-ranging applications of NPs may generate a slew of difficulties from an ecological, ethical, health, and safety standpoint (Rajput et al., 2018).

20. EFFECTS OF NANO PARTICLES ON GERMINATION

It is common to use a low-cost technique that moistens the seeds in a solution or combines them with a solid matrix, after which the seeds are dried and planted (Seed priming, Rehman et al., 2012; Arnott et al.,2021). There are different seed conditioning methods (Khalaki et al.,2021) to favor seed germination, such as seed immersion in water (hydropriming), in saline solutions (osmopriming), treatment with growth regulators (hormo-priming), treatment with temperature changes (matrix-priming), treatment with dissolved organic matter (bio-priming) and recently treatment with nanomaterials(nano-priming). Many nanoparticles have been used to alleviate seed dormancy and promote germination and germination vigor for agri- cultural and forestry species (Rahimi et al., 2016; Rhaman et al., 2022), since nanoparticles reach the seed coat and can improve the accumulation of reactive oxygen species, and therefore, they can activate biochemical processes involved into break seed dormancy and activate seed germination (Khan et al., 2022). The effects on the germination of different plant species are generally performed on petri dishes or in pots where the nanoparticles are mixed with the soil. The effect of nanoparticles on germination depends on several factors, such as Dose and treatment time. The doses and treatment time are crucial in establishing the beneficial effects and studying the toxicological and ecotoxicological aspects that may be generated in living organisms (Rhaman et al., 2022; Rutkowski et al., 2022; Salam et al., 2022b).

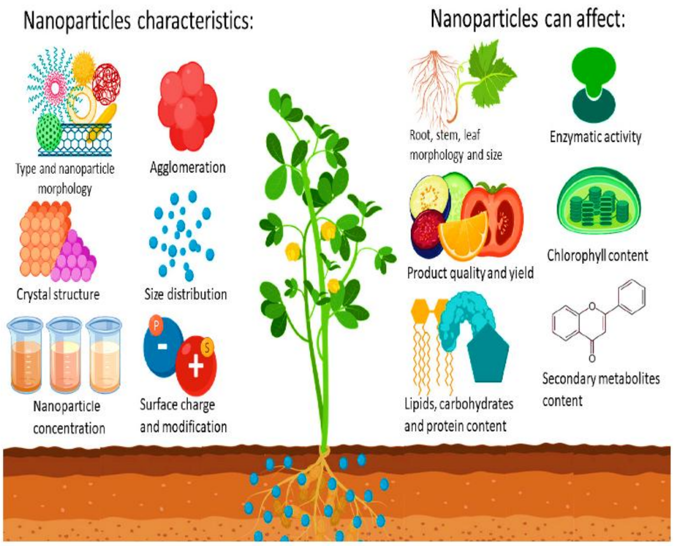


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Figure 7: Main characteristics of the nanomaterials and the possible toxicological effects they can induce in crops.

20.1. Inorganic nanoparticles with non-essential elements

Some nanoparticles of different elements have been used in agri- culture, such as Au, Al, Ce, Se, Si, Ti and Ag. Rock dust, a mixture of different minerals, has also been used as a germination improver for different plant species (e.g., Barrena et al., 2009; Arnott et al., 2021). Also, Au nanoparticle studies improved plant germination, as indicatedfor corn under 5 mg kg—1 concentration (Mahakham et al., 2016), cu- cumber and lettuce under 10 μg mL—1 (Barrena et al. (2009) and foronion (Acharya et al., 2019). Normally, Al is considered a toxic element for plants, inhibiting cell division in roots and thus blocking their growth; however, some experiments indicate that they favor an increasein biomass (Juhel et al., 2011; Hayes et al., 2020) and the growth of some plants such as soybean under flooding stress conditions. The Ce can positively affect germination, plant growth and increase chlorophyll and saccharide contents (Cao et al., 2017; Wu et al.,2017; Ramírez-Olvera et al., 2018; Murugadoss et al., 2023). Also, this element may favor gas exchange and improve CO2 assimilation due to the stimulation of stomata opening (Landa, 2021). Treatment with Se at low concentrations can improve crop yields (Bano et al., 2021). The Si can enhance the production of certain plants and mitigate biotic stress. (Naidu et al., 2023). Finally, Ti and Ag deserve a particular treatment due to the greater number of publications and are discussed in the following subsections.

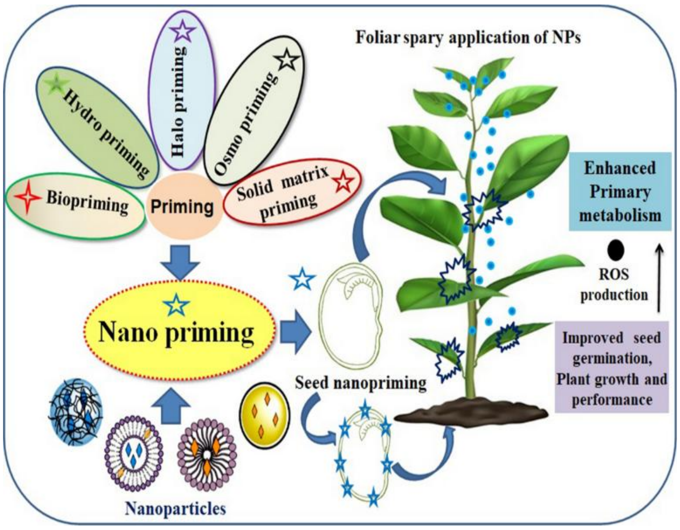

Figure 8: Seed priming is a pre-sowing treatment that causes a physiological change in the seed that permits it to germinate more rapidly

20.2. Silver nanoparticles

Silver nanoparticles have been widely used in various fields as an antimicrobial agent, as a component of shampoos and soaps, in waste- water treatment, food storage and as part of the composition of paints, among other applications (Rai et al., 2009; Wijnhoven et al., 2009).In the last two decades, Ag nanoparticles have also been widely used in agriculture with very positive results, improving the productivity of different crops. Thus, Ag nanoparticles can promote the growth and heat tolerance of T. aestivum (Iqbal et al., 2019), salinity tolerance; Nejatzadeh, 2021) and increase efficiency in water and fertilizer use (Lu et al., 2002). Also, these nanoparticles increase root nodulation and soil microbial diversity in a crop of V. sinensis, enhance chlorophyll concentration in Brassica juncea (Sharma et al., 2012), and the biomass of seedlings of Arabidopsis thaliana (Kaveh et al., 2013), and inhibits the growth of pathogenic bacteria in experiments with V. unguiculata (Vanti et al., 2020).Different publications studying the effect of Ag nanoparticles on germination are presented in Table 5. According to Mahajan et al.(2022), the results can vary depending on the crop type, particle size andthe nanoparticle's concentration, confirming that the application of Agnanoparticles may show positive and negative aspects on the develop-ment of cultivated plants. The crop type is an important factor because of its different nanoparticle sensitivity. For example, in experiments with the same dose of Ag nanoparticles with different crops, these nanoparticles did not significantly affect germination energy; germination capacity; length, number and abnormal sprouts of barley, peas and rape seeds. However, these Ag nanoparticles did benefit the germination energy of radish and cucum- ber seeds, especially under thermal stress conditions (Jaskulski et al.,2022).

The solubility of Ag nanoparticles can also be key to establishing their toxicity in different crops. In this sense, the higher the solubility of Ag, the higher the toxicity of the nanoparticles, as has been described in experiments with different crops such as T. aestivum, Sorghum bicolor, Lepidium sativum, S. alba, where the toxicity of $AgNO_3$ was higher than equivalent Ag nanoparticles (Matras et al., 2022). Similar results have been obtained in experiments with Ricinus communi. Toxicity on germination can increase due to the co-solvents used to obtain Ag nanoparticles, as Barrena et al. (2009) indicated in an experiment with L. sativa and C. sativus where sodium borohydride (2.64 mM) was used as a solvent and germination was decreased in comparison for Ag without solvent. The results depend on the type of co-solvent used, being able to increase the toxicity, for example, with a mixture of sodium borohydride and cysteamine hydrochloride, or decrease the toxicity with a mix of sodium borohydride and trisodium citrate (Matras et al., 2022), or even not reduce the toxicity of Ag nanoparticles with cysteine. Reducing agents such as xylose with Ag nanoparticles may limit microbial disease development and stimulate germination speed in experiments with S. lycopersicum (Rutkowski et al., 2022).

20.3. Titanium nanoparticles

Titanium occurs in nature in the form of TiO_2 and is mainly orga- nized in three different crystalline structures such as brookite (ortho- rhombic structure), anatase (tetragonal structure) and rutile (tetragonal structure) titanite. Titanium nanoparticles are used in various processes such as cosmetics manufacturing, food and medicine (Grand and Tucci,2016). Titanium nanoparticles applied to the soil can improve soil salinity and increase leaf length and plant dry weight, as proven in a *V. faba* crop (Fatima et al., 2021). The effects of Ti nanoparticles on plant germination are presented in Table 6. In general, the effects of Ti nanoparticles have been studied to a lesser extent than Ag nanoparticles, but the conclusions drawn are very similar in view of the current knowledge. In this sense, the available data indicate that the presence of Ti nanoparticles does not affect germination as in the case of T. aestivum,B. napus and A. thaliana (Larue et al., 2011); B.

campestris, L. sativa and *P.vulgaris* (Song et al., 2013a); and S. lycopersicum (Song et al., 2013b). This may be attributed to the non-penetration of nanoparticles into the seed coat and endosperm, described in a study with S. lycopersicum (Song et al., 2013b) and may be attributed to agglomeration of the nano- particles (Cox et al., 2016). However, Ti nanoparticles penetrated plant tissues with crops such as B. campestris, L. sativa and P. vulgaris (Song et al., 2013a). In this regard, Du et al. (2011) indicated that only a small part of TiO2 nanoparticles can penetrate the rhyzoderm of primary roots in experiments with T. aestivum. strength leads to an increase in salinity, which causes plant stress. In this sense, nanoparticle addition can reduce this abiotic stress (AbdelLatef et al., 2018; Iqbal et al., 2020). For example, Ti nanoparticles (nTiO2) can reduce the adverse effects of salinity on broad beans (Vicia faba) (Abdel Latef et al., 2018). This similar effect was also reported by Hojjat et al. (2019) and Nejatzadeh (2021) for Ag nanoparticles on bitter vetch (V. ervilia) and summer savory (Satureja hortensis), respectively. The effects of temperature and humidity are less well studied, although the temperature may alter the interaction of nanoparticles such as Zn with plants (Lo´pez-Moreno et al., 2017).Treatment times also vary widely, ranging from 24 h to 150 days, depending on the type of crop and the type of experiment and variables to be studied, as reviewed by Mahapatra et al. (2022).

20.4. Comparison of nanoparticles added together.

The results indicate that adding bimetallic nanoparticles favors germination; for example, the presence of ZnS/AgS nanoparticles favors the germination of T. aestivum and O. sativa concerning the control samples, with only distilled water (Iqbal et al., 2022). However, as with individually added nanoparticles, the effects on germination are con- centration dependent. Khan et al. (2021) synthesized ZnO nanoparticles with different Ni concentrations and found that the germination of *T. aestivum* increased when adding Ni concentrations ≤3%. However, with Ni at 5%, there was a sharp decrease in the germination percentage. Germination vigor, root and leaf length follow the same trend.

20.5. Comparison of nanoparticles added individually.

In this kind of experiment, the effects on the germination of two or more nanoparticles are compared by establishing toxicity sequences. For example, when comparing the toxic impact of Ag and Ti nanoparticles, Ag nanoparticles are more toxic than Ti nanoparticles (Cox et al., 2016). Similar results were obtained by Song et al. (2013b), who indicated that Ag nanoparticles inhibit the germination of S. lycopersicum while Ti nanoparticles have no such toxic effect on seed germination.On the other hand, El-Temsah and Joner (2012) indicated that Fe nanoparticles could be used at low concentrations favoring germination, while Ag nanoparticles inhibit the germination of Fe nanoparticles of *L. usitatissimum*, *L. perenne* and *H. vulgare*. Davydova et al. (2019)determined that both Fe and Zn nanoparticles have a positive effect on the germination of T. aestivum, but Zn has a greater positive effect. Sequences of toxicity or positive effects on the germination of different nanoparticles are also established. For example, Yang et al.(2015) indicated that the oxides of 7 elements (Fe, Si, Ti, Al, Ce, Zn andCu) did not affect the germination of maize and rice, while CuO and ZnO significantly inhibited root elongation at 2000 mg L—1, and Al was slightly toxic only to maize. Toxicity was found only with the nano- particles and not with the soluble elements of Cu2+, Zn2+ and Al3+. In general, these effects depend on the type of crop; in this regard to study the effect of different nanoparticles (Ti, Zn, Al and Cu) on four plants (radish, cucumber, tomato and alfalfa). They indi- cated that the effects depend on the type of culture and the concentra- tion of the metal nanoparticles. Zinc nanoparticles had the highest inhibitory effect among the different metals, followed by Cu nano- particles. However, opposite results were also found, indicating that Zn nanoparticles have a greater positive impact on the germination of *C. reticulata* than Cu nanoparticles (Hussain et al., 2017). Similar results were obtained by Singh and Kumar (2019), establishing the following sequence of toxicity in germination studies with R. sativus (CuO > CuO+ ZnO > ZnO); and by Ko and Kong (2014) with the toxicity sequence: CuO > ZnO > NiO > Co3O4>Fe2O3>TiO2. The increased toxicity of Cu nanoparticles has also been shown in experiments with different types ofsoils; Kolesnikov et al. (2021a) indicated that toxicity on R. sativus germination in a Cambisol-type soil follows the sequence Cu ≥ Zn > Ni; similar results to those obtained in an Arenosol (nanoparticle concen- tration of 100 mg kg—1), although this sequence is dependent on nano- particle concentration (Kolesnikov et al., 2021b).

21. Mechanisms of Action of NPs in Plants

Although NPs have a wide range of applications in agriculture, the majority of NPs are hazardous to plants when present in high concentrations. The uptake, accumulation and interference of NPs with key metabolic processes in different plant tissues may have positive or negative effects on plants, depending on their dosage, movement, characteristics, and reactivity.

21.1. Uptake of NPs

High concentrations of NPs can penetrate plant cells and cross the plasma membrane; thus, this may interfere with key cellular activities; Mirzajani et al., 2013). NPs can reach plant tissues through the root system or above-ground parts such as root junctions and wounds. As a carrier, NPs must pass through several physiological barriers until they are taken up by the plant and translocated. Plant cell walls, which are made up of cellulose, allow small NPs, ranging between 5 and 20 nm in size, to pass through into the plant cells (Dietz and Herth, 2011).

Some NPs have been shown to develop larger pores in the cell wall to enter the cell (Navarro et al., 2008). NPs can be transferred to other plant tissues via the apoplastic and symplastic pathways (Etxeberria et al., 2006; Ma et al., 2010). Wong et al. (2016) suggested a lipid exchange mechanism for NPs transport into plant cells. The size, magnitude, and zeta potentials of NPs are important to determine their delivery in plant cells.

21.2. NPs-Plant Interaction Pathways

NPs may affect plant metabolism by delivering micronutrients (Liu and Lal, 2015), gene regulation (Nair and Chung, 2014), and interfering with several oxidative processes in plants (Hossain et al., 2015). Excessive contents of NPs can generate ROS; thus, interfering with the oxidative mechanism; while other pathways have yet to be deciphered. The NPs can disrupt the electron transport chain in mitochondria and chloroplast, causing an oxidative burst and an increase in ROS levels (Pakrashi et al., 2014; Cvjetko et al., 2017). The rate of carbon fixation is reduced in response to stressful conditions; thus, this increases photoinhibition, potentially leading to the overproduction of superoxide anion radicals and H2O2 in the photosystem (Foyer and Noctor, 2005). When ROS is generated as a result of NPs, all biological components are affected causing protein changes, lipid peroxidation, and DNA damage (Van Breusegem and Dat, 2006).

Several studies have found an increase in lipid peroxidation and DNA damage in plants while interacting with NPs (Atha et al., 2012; Saha and Dutta, 2017). The increase in ROS levels can cause apoptosis or necrosis, resulting in plant cell death (Faisal et al., 2013). Despite its destructive nature, ROS play a role in biological activities, including stress tolerance (Sharma et al., 2012a). The balance between ROS generation and scavenging determines whether ROS has a destructive or signaling function. The cells have developed a robust antioxidant mechanism to precisely control the quantity of ROS. Enzymatic (SOD, CAT, and guaiacol peroxidase) and non-enzymatic (ascorbate, glutathione, carotenoids, tocopherols, and phenolics) antioxidants are attributed to defense mechanisms in plants (Sharma et al., 2012b). Several studies have demonstrated that plants exposed to NPs produce more antioxidant molecules (Jiang et al., 2014; Costa and Sharma, 2016). Plant stress response signaling can also be influenced by phytohormones (Mengiste et al., 2010; O'Brien and Benková, 2013; Sham et al., 2019).

Plant hormones are endogenous molecules involved in the regulation of plant development and stress tolerance (Sham et al., 2017). In response to abiotic stresses, different hormonal pathways can be activated or suppressed (Kwak et al., 2006; O'Brien and Benková, 2013). In red pepper (Capsicum annuum), cytokinin levels increased in response to AgNPs stress; while in cotton (Gossypium sp.), a decrease in the levels of auxins and ABA in response to CuO NPs was detected. This suggests that NPs affect plant hormonal balance and plant metabolism. Several studies have demonstrated that NPs can also affect the content and activity of photosynthetic pigments in plants (Perreault et al., 2014; Tripathi et al., 2017c). High concentrations of NPs have a negative impact on photosynthesis, resulting in growth retardation or death in plants (Tripathi et al., 2017c).

21.3. Future Prospects on NPs for Enhancing Crop Tolerance to Abiotic Stress

Nanobiotechnology has the potential to improve stress tolerance, stress sensing/detection, targeted delivery and controlled release of agrochemicals, transgenic events, and seed nanopriming in plants (Wu and Li, 2022). Such nanomaterials free of HMs and high dispersibility can be developed for agricultural use. Future research on evaluating the biological effects of nanozymes i.e., Mn3O4 NPs in plants under stress conditions should be on top of our priorities. Mechanisms underlying nanopriming-induced seed germination, breaking seed dormancy, and their interactions with seeds have to be investigated. Understanding how NPs improve plant stress tolerance will enable researchers to design tailor-made nanomaterials targeting agricultural challenges. In addition, nanomaterials have no doubt a bright future ahead, especially when it comes to their functionality in plants. For example, Santana et al. (2020) have developed a targeted delivery approach using nanomaterials to convert chloroplasts into "chloroplast factory" for better plant photosynthesis under low light conditions. The use of nanomaterials for CRISPR-Cas genome editing in cargo delivery (Demirer et al., 2021) will increase the efficiency of genetic engineering to enhance plant stress tolerance. Developing policies and regulations could help manage biosafety hazards associated with the use of nanomaterials in agriculture. We believe that nanomaterials will play a crucial role in the future of agriculture.

22. Future Prospects and summary:

Based on the literature investigated in this review, the use of nanoparticles as nanofertilizers or nanopesticides were shown to have both beneficial and negative effects on plant- associated microbial populations as well as crop and soil properties. The implications of exposing agricultural environments to nanoparticles can therefore be beneficial or detrimental with respect to the health of agroecosystems and as a result of downstream consumption of crops. Moreover, the environmental risk assessment of nanoparticles is in its infancy. Thus, further research studies investigating the impact of different types and doses of nanoparticles, applied under varying environmental conditions, on microbial communities and function, especially long-term, are necessary. Despite the rise in the manufacturing of nanoparticles for agricultural applications, the majority of risk assessment testing is conducted in-vitro using cells rather than animals as test subjects. Therefore, more research on soil and human health implications is necessary due to the ambiguities surrounding the negative consequences of nanoparticle applications. In the context of impact of nanofertilizers and nanopesticides, plant-associated microorganisms indicative of healthy/unhealthy crops and soils should be employed as sensitive biomarkers to assess the environmental risk of these nanomaterials. Moreover, prospective studies should investigate the impact of nano-based agricultural amendments under different conditions such as crop type, soil properties and microbial community dynamics for the compilation of a database that can provide a case- by-case basis for precision agricultural practices incorporating the utilization of nanoparticles.

The potential role played by several NPs in alleviating abiotic stress-induced damage and improving plant development and crop yield is under intense investigation. NPs, such as TiO2, SiO2, and Ag NPs, can reduce the negative effects of abiotic stress by activating plant defense mechanisms via the induction of ROS production and phytotoxicity. NPs, given their small size, can also easily penetrate plant tissues, after which they positively influence plant morphological, physiological, and biochemical processes, promote plant development, and improve crop productivity in plants under various abiotic stresses. Moreover, NPs have a large surface area that improves the absorption and delivery of various targeted nutrients. Nevertheless, the applications of NPs in crop improvement and sustainable agriculture are still at an early stage of development, and the current research in the field is insufficient and, to some extent, inconsistent (Rajput et al., 2021). Therefore, additional investigations must explore the following issues, which will help limit the undesirable effects of NPs on ecosystems and crops: (a) the reaction of NPs with plants and metabolic process at the molecular and cellular levels, and optimization of NPs size and level before practical application in the field; (b) the effects of NPs and their possible toxicities in different plant species; (c) the impact of NPs on gene regulation and expression in plants under various abiotic stresses; (d) the behavior and fate of NPs in plants and the environment; (e) the effects of soil properties and different plant species on the efficiency of NPs; (f) the classification of NPs as stress initiators or stress in activators; and (g) the combined effects of NPs with other active ingredients and biotic stresses in plants.

KEY SUMMARY:

Nanotechnology is emerging as a promising tool for advancement in agriculture. Nanomaterials, with at least one dimension of 100 nanometers or less, have unique optical, magnetic, electrical, and mechanical properties. Their high surface area-to-volume ratio also makes them highly reactive.

The use of Nanotechnology in agriculture enables efficient disease detection and management, precision farming through nano-sensors, enhanced productivity through nano-fertilizers and pesticides, and improved food quality and safety through innovative packaging materials. Hence, the use of nanotechnology in agriculture is significant in order to meet the changing needs and domains of providing food to the growing population of the world.

Applications of Nanotechnology in Agriculture

In agriculture and food systems, nanotechnology has emerged as a powerful set of tools that allows enhanced productivity, disease/pest resistance, nutrient absorption, and food safety. Major applications of nanotechnology across the crop production value chain include:

Nano fertilizers: *Conventional fertilizers have low nutrient use efficiency as the majority of applied nutrients are wasted and cause environmental pollution.*

Nano-encapsulated fertilizers control the release rate of nutrients that match the crop's needs over time.

Slow and steady nutrient delivery reduces losses. Nanocarriers also protect nutrients from soil immobilisation.

Nano pesticides*: Nanoscale pesticide formulations enhance solubility, dispersion, target-specific delivery and efficiency compared to conventional pesticides.*

Nanocapsules, *nanogels, and emulsions allow the slow and sustained release of active ingredients.*

Lower doses are effective and toxicity is reduced.

Nano-sensors: *Miniaturised optical, electrochemical and magnetic nano-sensors monitor soil quality, crop growth environment, plant pathogens, moisture levels etc. in real-time.*

Farmers can take quick action and move towards precision agriculture with the help of networked nano-sensors.

Smart delivery systems:

- *Nano-porous zeolites, carbon nanotubes, cellulose nanofibers etc. act as smart carrier systems for controlled and targeted delivery of genes, DNA, growth hormones, herbicides and other agrochemicals to plants, this improves efficiency.*
- *Anti-microbial Nano-coating: Silver nanoparticles applied as coatings on greenhouse glass, plastic films, and irrigation pipes prevent microbial buildup.*
- *This avoids decay and enhances the durability of farming infrastructure.*
- *Water purification: Magnetic nanoparticles, carbon nanotubes and nano filters enable rapid decontamination of water from pesticides, fertilizers, pathogens etc. which is then safely reused for*

irrigation.

- *Plant disease diagnostics: Nano barcodes and nanoprobes coated with antibodies detect plant pathogens like bacteria and viruses quickly and accurately compared to conventional techniques.*

Rapid diagnostics facilitate early disease prevention.

Seed germination: Nano priming of seeds with zinc, titanium dioxide, and silica nanoparticles speeds up germination rates and plant growth by penetrating the thick seed coat and enhancing enzyme metabolism.

Food packaging: Nanocomposite films with nano clays and cellulose nanofibers improve mechanical strength, barrier properties, heat resistance and biodegradability of food packaging compared to conventional polymer packaging.

Crop protection:

- *Silica nanoparticles applied on leaves shield the plants from high temperatures and strong UV radiation.*
- *Nano-coatings on fruits restrict oxygen and moisture penetration to delay ripening and prevent spoilage during storage.*

Nanotechnology Applications in Food Processing

Nanotechnology promises to become a major driver of innovation in agriculture, food processing, and packaging. Nanotechnology is enabling revolutionary changes across the food manufacturing value chain:

Encapsulation and delivery:

- *Nano-encapsulation of nutrients like vitamins, minerals, antioxidants and flavours in the food matrix through techniques like nanoemulsions, nanoliposomes, bilayer vesicles, etc. improves their stability and controlled delivery in food products.*
- *Food safety: Nanosilver particles incorporated into food containers and packaging films provide antimicrobial protection and avoid contamination.*
- *Magnetic nanoparticles bind and detect pathogens like Salmonella and E. coli in food samples within minutes for quality checks.*
- *Product development: Nanoscale self-assembled structures of lipids, proteins and polymers can mimic food properties like texture, taste, and appearance.*
- *This enables the design of low-fat or fat-free food formulations.*

Enzyme Immobilization: *Fixing enzymes over nanomaterials like silicate nanoparticles retains their activity and reusability during the synthesis of sugar syrups, organic acids, and amino acids used in food processing.*

Nanomagnets can retrieve immobilised enzymes.

Nutrient absorption: *Reducing nutrients like vitamins, minerals and supplements into nanoforms enhances* *their bioavailability, solubility and absorption in the body.*

- *Nanoencapsulation also improves flavour.*
- *Packaging: Oxygen scavenging nanopackaging absorbs oxygen to prevent spoilage of food items.*
- *Nanosensors integrated packaging detects food contamination and shows changes through colour or fluorescence.*

Processing equipment: *Nanofilters remove microscopic contaminants during the processing of wine, beer, and fruit juices.*

- *Nanocoatings minimise bacterial adhesion on machines and prevent corrosion.*
- *Food Nano-sensors: Low-cost printed nanosensor arrays based on gold and silicon nanoparticles change colour to detect gases released during food decomposition.*
- *Portable nanosensor kits identify contaminants and allergens.*

Cleansing agents*: Silver nanoparticles exhibit strong antibacterial activity against foodborne pathogens like E. coli, Listeria, and Salmonella.*

Coatings and nanosprays keep processing equipment sterilised.

Smart packaging: *Nanosensors and RFID nanotags integrated into packaging detect gases released by spoiling foods like meat, fish, etc. and communicate through colour-changing indicators; this improves food shelf-life.*

I. Meat Processing

Application	*Nanomaterials used*	*Purpose*
Antimicrobial coatings	*Silver, magnesium oxide, and chitosan nanoparticles*	*Reduce biofilm formation*
Smart packaging	*Palladium nanoparticles*	*Sense spoilage gases*
Meat tenderization	*Enzyme nanoparticles*	*Catalyze protein breakdown*
Time-temperature sensors	*Nanoparticles dispersed in edible films*	*Monitor product freshness*

II. Bakery Products

Application	*Nanomaterials used*	*Purpose*
Nutrient delivery	*Chitosan, soy protein, PLGA nanoparticles*	*Prevent degradation during processing*
Fat replacers	*Nanocellulose, nanoclays*	*Reduce fat content in cakes, pastries etc.*

Antimicrobial packaging	*Silver nanoparticles*	*Prevent microbial spoilage*
Dough conditioning	*Zinc oxide nanoparticles*	*Improve handling properties*

III. Horticulture

Application	*Nanomaterials used*	*Purpose*
Coatings	*Aloe vera nanofibers*	*Reduce moisture loss*
Antibrowning agents	*Nanocapsules with antioxidants*	*Prevent enzymatic browning*
Condition monitoring	*Nanosensors*	*Detect temperature changes*
Smart packaging	*Polymer nanocomposites*	*Control gas exchange*

IV. Beverages

Application	*Nanomaterials used*	*Purpose*
Water treatment	*Silver nanoparticles*	*Disinfect drinking water*
Toxin detection	*Gold nanoparticles*	*Sense contaminants in beverages*
Gas barrier	*Carbon nanotubes*	*Prevent oxidation in beer bottles*
Packaging material	*Nanoclays*	*Enhance barrier and strength*

Key Challenges of Nanotechnology in Agriculture

While offering tremendous benefits, some key challenges currently inhibit the large-scale adoption of nanotech in agriculture:

Toxicity concerns: *The impacts of nanomaterials on soil quality, microbial activity and human health require more evaluation through life cycle analyses and can also trigger the production of free radicals.*

- *Nanomaterials reaching the land have the potential to contaminate soil and migrate into surface and ground waters.*
- *High costs: The R&D and specialised manufacturing systems required to engineer nanoproducts make initial investment prohibitive for small companies.*
- *Scalability: A large variety of nanomaterials are still only being produced in lab quantities. Methods*

for controlled, scalable synthesis with reliable properties have to improve.

- *Regulations: Regulatory uncertainty due to lack of standardised safety data and nano-specific regulations deters commercialisation.*
- *International harmonisation of regulations would help.*
- *Lack of awareness: Understanding of nanotechnology remains low among farmers. Effective communication regarding costs versus benefits for different applications is needed.*

Skill shortage: *There is limited interdisciplinary expertise combining domains like nanoscience, agriculture, and food technology. Capacity building is required.*

- *Government Initiatives on Nanotechnology in Agriculture*
- *Realising the potential of nanotechnology, India has established dedicated nanotechnology programs and research centres:*

Nano Mission: *Launched nanotechnology research centres like the Centre for Nano Science and Engineering (CeNSE) at IISc Bangalore, which works on nano-fertilizers and nanotech food packaging.*

ICAR Initiatives: *The Indian Council for Agriculture Research established Nanotechnology Centres at IARI and IVRI to develop nano-biosensors, nano-pesticides, and nanocapsules for nutrient delivery.*

- *IFFCO placed India first in the world in Nano Urea and Nano DAP production.*
- *Nano Urea is sprayed not on the ground but on the plants, which leads to a zero possibility of destruction of natural elements or earthworms present in the soil.*

Nano-fertilizers: *IARI developed nanoparticles of zinc, chitosan, and silica as nano-fertilizers for improving crop growth and yield.*

Nano-sensors: *ICAR funded the development of nano biosensors at IIT Kharagpur for detecting pesticide residues in food.*

Nano-pesticides: *Tamil Nadu Agriculture University synthesised nanoparticles of herbal extracts as an eco-friendly, non-toxic nano-pesticide.*

Toxicity evaluation: Karumanchi University assessed the impacts of nano-scale zinc oxide on soil microbial activity.

International collaboration: *Indo-UK project between the University of Birmingham and IIT Delhi on nano-sensors to monitor soil and crop health.*

Way forward

- *Nanotechnology has exciting potential to enhance agriculture and the entire food value chain. Here are some future possibilities:*

Multifunctional nanosystems: *These systems can simultaneously improve crop yield, damage resistance, water efficiency, and fertilizer utilisation.*

Large-scale networks of nanosensors: *These networks will provide real-time monitoring of soil, plant health and food quality across the supply chain.*

- *Smart nano-pesticides and nutrients are responsive to plant biochemistry for precise dosing and minimized toxicity.*
- *AI-guided automation will enable data-driven dynamic optimisation of nanomaterial dosages and applications.*

Edible nano-coatings: *To allow self-cleaning and anti-browning effects to produce.*

- *Nano-enabled urban agriculture: Vertical farms, nano-greenhouses and hydroponics to maximize roductivity.*
- *Nanotech-derived new functional ingredients: Like colourants, textures, flavours, and vitamins synthesized using nano processes.*
- *Active packaging with colour-changing nanosensors: To give visual spoilage alerts to consumers.*
- *With benefits like increased crop yield, reduced waste, and sustainability, nanotechnology can play a pivotal role in shaping the future of agriculture in India.*

21. AUTHOR DECLARATION:

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

28. AUTHOR DISCLAIMER

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during writing or editing of this manuscript.

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Authors have declared that no competing interests exist.

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