

NANO-ENABLED APPROACHES FOR MODULATING PLANT GROWTH, METABOLISM AND STRESS RESILIENCE: A COMPREHENSIVE REVIEW

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ABSTRACT

‘Nano’ a Greek word that means ‘dwarf’ The word ‘nano’ is used to refer a billionth part of one meter. It’s generally used for materials of size between 1 to 100 nm. They are referred as nanoparticles or the nanomaterials. It behaves as one unit with respect to its transport and other properties. It can exhibit specialized physical and chemical properties. Nano is a molecules or molecular clusters into structures to create materials, devices with new or vastly different properties. This platform entails the growth of methodologies to a variety of low-cost nanotech applications for improved germination of seeds, development and acclimatization to environments. Several researchers have found that various nanomaterials, like TiO₂, SiO₂, ZnO, nano-ceria, Fe₂O₃, S, Au, MgO, Ag NPs, chitosan, graphene oxides etc., reduce the negative impacts of abiotic stresses on agricultural plant species like barley, sugar beet, potato, maize, *Arabidopsis thaliana*, alfalfa and flax, etc. Nanotechnology with its miniature dimension has revolutionized agriculture and food industries by providing novel farming techniques, disease and deficiency detecting tools, modified tools to enhance nutrient absorption and bioavailability, sustained and controlled release of pesticides, herbicide, fertilizers, etc. Key advancements highlighted include nano-priming to enhance seed germination, controlled-release nano-fertilizers, and precision pesticide delivery systems. Critical challenges such as potential environmental toxicity, bioaccumulation, and the absence of standardized regulatory frameworks are also evaluated. Ultimately, the balanced integration of nanotechnology promises to revolutionize sustainable farming practices and significantly optimize resource-use efficiency.

KEYWORDS: Nano particles, Nano-priming, Seed germination, Seed Invigoration, Plant health

1. INTRODUCTION

Agricultural scientists are facing a wide spectrum of challenges such as stagnation in crop yields, low nutrient use efficiency, declining soil organic matter, multi-nutrient deficiencies, climate change, shrinking arable land and water availability and shortage of labour besides exodus of people from farming. A challenge for global food and nutrition security is to feed the world population with nourishing food (Quasem *et al.*, 2009; Ghaly, 2009). Therefore, in the future, emphasis should be laid on production of high-quality food with the required level of nutrients and proteins (Pijls *et al.*, 2009) Nanotechnology is the Design, Fabrication and Utilization of materials, devices and systems through control of matter on the nanometer length scale and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale. It is now more properly labeled as "molecular nanotechnology" (MNT) or "nano-scale engineering". By taking advantage of quantum-level properties, nanotechnology allows for unprecedented control of the material world, at the nanoscale, providing the means by which systems and materials can be built with exact specifications and characteristics, allowing materials to be lighter, stronger, smarter, cheaper, cleaner and more precise (Ghaly and Alkoik, 2010).

Nanotechnology has the potential to advance agricultural productivity through genetic improvement of plants, delivery of genes and drug molecules to specific sites at cellular levels, and nano-array based gene-technologies for gene expressions in plants and animals under stress conditions. The potential is increasing with suitable techniques and sensors being identified for precision agriculture, natural resource management, early detection of pathogens and contaminants in food products, smart delivery systems for agrochemicals like fertilizers and pesticides, smart systems integration for food processing, packaging and other areas like monitoring agricultural and food system security. Further developments in nanotechnology in this sector can be expected to become the main economic driving forces in the long run and benefit consumers, producers, farmers, ecosystems, and the

general society at large.

Nano Science: The study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.

Nano Technology: The design, characterization, production and application of structures, devices and systems by controlling shape and size at the nanometer scale” Nanotechnology is the design, fabrication and utilization of materials, Structures, devices and systems through control of matter on the nano meter length scale and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale In at least One dimension. "Nanotechnology is the exploration and management of matter at the nanoscale, where distinct phenomenon permits revolutionary applications," according to the US National Nanotechnology Initiative (NNI) 2004. Nanotechnology may be defined as understanding and control of matter at dimensions between approx. 1 and 100 nanometers, where unique phenomena enable novel applications. (National Nanotechnology Initiative, 2007, The European Commission).

2. IMPORTANCE OF NANOTECHNOLOGY

The second most important area for the deployment of nanotechnology was the improvement of agricultural productivity, with crop production as one of the highest priorities in the global nanoscale research agenda, among the technological interventions considered for their contribution to the millennium development goals. This ranking acknowledges that food security problems cannot be solved by incremental gains alone through conventional breeding and input management. The field is still in its infancy but the direction is one which can transform agriculture and the food system as a whole instead of just improving it (Roco, 2001). Much of this promise stems from the observation that biological systems already operate with a molecular sophistication that engineered devices have not yet achieved. Nature is a nanoscale assembler, transporter and regulator of matter and the discipline provides a route to emulate that precision with an efficiency beyond human design. Working at this scale allows for the construction of molecular architectures with a precision, flexibility and economy not achievable with bulk-scale fabrication, opening up the possibility for inputs and devices designed for specific physiological targets within the plant. In practice this capability addresses several long-standing weaknesses in farming systems. The effectiveness of applied inputs can be significantly improved, reducing the losses associated with the use of conventional fertilizer and agrochemicals. Nanoscale tools enable responses to environmental constraints that have traditionally limited yield. Improvements in productivity are possible within the existing ecological limits rather than expansion of area cultivated or increased input loading. Detection and management of crop disease can be facilitated with sensing platforms that can detect infection before visible symptoms appear and formulations that can improve nutrient solubility and root uptake can improve the mineral acquisition capacity of crops from the soil (Alfadul et al., 2017). These developments are of direct relevance, in particular, to seed science. Seed is the one point where a small, accurately delivered intervention can affect the whole crop cycle that follows. It's an efficient target for treatment at the nanoscale. Priming, coating and nanocarrier-mediated delivery at the seed stage allow modification of germination behavior, early vigor and stress tolerance with minimum material input, closely matching the precision and economy that defines the discipline. The integration of artificial intelligence (AI), machine learning, and precision-farming technologies can further strengthen nanotechnology-enabled agricultural systems by supporting data-driven crop monitoring, resource management, and timely decision-making (Geetanjali and Singh, 2025; Taqvi, 2025).

3. MEMOIR OF NANOTECHNOLOGY

The American physicist and Nobel Prize laureate Richard Feynman introduce the concept of nanotechnology in 1959. During the annual meeting of the American Physical Society, Feynman presented a lecture entitled “There’s Plenty of Room at the Bottom” at the California Institute of Technology (Caltech). In this lecture, Feynman made the hypothesis “Why can’t we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin?”, and described a vision of using machines to construct smaller machines and down to the molecular level. This new idea demonstrated that Feynman’s hypotheses have been proven correct, and for these reasons, he is considered the father of modern nanotechnology. After fifteen years, Norio Taniguchi, a Japanese scientist was the first to use and define the term “nanotechnology” in 1974 as: “nanotechnology mainly consists of the processing of separation, consolidation, and deformation of materials by one atom or one molecule”. After Feynman had discovered this new field of research catching the interest of many scientists, two approaches have been developed describing the different possibilities for the synthesis of nanostructures. These manufacturing approaches fall under two categories: top-down and bottom-up, which differ in degrees of quality, speed and cost.

✓ **1986:** G. Binnig and H. Rohrer: Invented Scanning tunnelling microscope (STM), tool allows the sensing of matter at nanometre scale

✓ **1987:** First nanotech symposium held

✓ **1989:** First national conference on nanotech (control of solid-state structure in molecular materials by electrostatic self-assembly, atomic imaging and positioning, hopes and fears of an environmentalist for nanotechnologies, risks, economic consequences, etc.)

✓ **1991:** Dr. Drexler, first Ph.D in nanotechnology awarded in Cambridge University, United States

✓ **2000:** Lucent and Bell Labs with Oxford University; created the DNA motor, first nano-biotechnological gadget.

4. PROPERTIES OF NANOPARTICLES

The main parameters of interest with respect to nanoparticle safety are Physical and chemical properties

Physical properties: Size, shape, specific surface area, Agglomeration/aggregation state, Size distribution, Surface morphology/topography, Structure, including crystallinity and Solubility

Chemical properties: Structural formula/molecular structure, Composition of nanomaterial (including degree of purity, known impurities or additives), Phase identity, Surface chemistry (composition, charge, tension, reactive sites, physical structure, photocatalytic properties, zeta potential) and Hydrophilicity/lipophilicity.

- **Specific surface area:** Reactions of particles mainly occur at their surfaces therefore, the molecules and atoms at the surface play an important role. Generally, surface atoms and molecules are different from those in the bulk materials because they may be unsaturated or bonded to the surrounding species such as solution species, gas molecules or near solid materials rather than to the bulk atoms (Burlinson *et al.*, 2004). In the case of nanoparticles, as the particle size decreases, the proportion of atoms and molecules at the surface or near-surface regions increases (Nel *et al.* 2006., Lu, 2002).

- **Surface charge:** The surface charge of particles is an important feature which determines their dispersion/stability and affects their mobility in the environment (Darlington *et al.* 2009). The surface charge of metal oxide particles is known to be dependent on the pH, composition and ionic strength of the surrounding solution and adsorbed species on the particle surface (Degen and Kosec, 2000; Illes and Tombacz, 2006).

- **Dissolution:** Solubility and dissolution kinetics of particles are size dependent (Borm *et al.* 2006). As mentioned earlier, a decrease in the size of particles leads to higher surface area and consequently larger free energy at the surface of nanoparticles compared to bulk materials. For particles less than 1 μm , the surface free energy becomes very large which may affect the thermodynamics of dissolution. This excess energy at the surface of particles is expressed as surface tension. In theory, the solubility of solids depends on the surface tension, which is correlated with the specific surface area and thus also with the particle size (Stumm and Morgan, 1996). A number of studies have been made early in the 20th century to measure solubility of finely divided solids as a function of particle size.

- **Deposition:** Deposition is defined as the transport of particles to an immobile surface followed by attachment (Lecoanet *et al.*, 2004). Two main processes may cause deposition of colloids and therefore nanoparticles in soil. Firstly, straining or physical filtration where nanoparticles are larger than the pore size and are trapped; and secondly, true filtration (Nowack and Bucheli, 2007). There are different hypotheses about the influence of particle size on the deposition process. One view argues that, based on electric double layer interactions, the deposition rate is dependent on particle size, and nanoparticles undergo collisions with the collector more frequently than larger particles due to Brownian motion (Hydutsky *et al.*, 2007).

- **Mobility:** The mobility of nanoparticles in soil is one of the major factors which may affect their availability to soil biota, their distribution through the soil profile, and effective persistence in soil (Lead and Wilkinson, 2006). As well as the characteristics of the soils such as pH, clay content and type, amount and type of soil organic matter, ionic strength and composition of the soil solution, and flow velocity (Schrack *et al.* 2004).

- **pH:** The mobility and aggregation of nanoparticles in soils are strongly affected by the surface charge of the nanoparticles. The authors showed that where the pH of the percolating solution was within one unit of the pH of the nanoparticles, transport was limited due to aggregation and deposition (Guzman *et al.* 2006). Thus, if a particular nanoparticles product is to remain mobile in the soil environment, it will be important to alter the surface properties of the particle so that the PZC is well outside normal soil pH values.

- **Ionic strength of the soil solution:** Concentration of salts in the soil solution may strongly affect the aggregation as well as deposition of nanoparticles. As the ionic strength of the soil solution increases, electrostatic repulsion between particles reduces and Vander Waals attractions outweigh the repulsion (Hotze *et al.*, 2010). Aggregation and deposition of manufactured nanoparticles may be influenced by the ionic composition of the soil solution was already observed for natural nanoparticles (Perdrial *et al.*, 2010). Divalent ions such as Ca^{2+} or Mg^{2+} have been shown to be more effective in speeding up kinetics of particle deposition than monovalent ions like Na^+ and hence particle deposition occurs at much lower concentrations of Ca^{2+} than Na^+ (Chen and Elimelech, 2007). The same phenomenon may be expected to occur for manufactured nanoparticles in soil solution. Saleh *et al.*, 2008 reported enhanced deposition of Fe nanoparticles in sand columns with an increase in the concentration.

- **Soil texture:** Interactions of nanoparticles with soil minerals can affect their mobility, bioavailability, reactivity and persistence in soils. The complexity of soil minerals makes it difficult to study the mechanisms involving in the reactions of soil minerals with nanoparticles. Nevertheless, a few recent investigations have addressed the effect of clay minerals on the mobility and retention of nanoparticles in soil suspensions or soil columns (Cornelis *et al.*, 2010; Cornelis *et al.*, 2011).

- **Manufactured nanoparticles and soil organisms:** Environmental exposure models have predicted that soils are the main environmental compartment receiving nanomaterials, successful application of nanoparticles in different industrial sectors has generated interest in the application of nanoparticles in agriculture for targeted release of agrochemicals or efficient nutrient utilization which may enhance plant growth and health (DeRosa *et al.*, 2010; Nair *et al.*, 2010). Therefore, enhanced abundance of nanoparticles in the environment has primed researchers to be concerned about the possible negative or positive effects of manufactured nanoparticles on seeds. Moreover, biological uptake mechanisms, translocation, transformation and degradation of nanoparticles

via soil organisms and plants can be important pathways in the life cycle of manufactured nanoparticles which influences their fate in soil systems (Lin *et al.*, 2010). Although high rates of application can provide important information on the toxicity mechanisms, it cannot predict the dose-response relationship at environmentally relevant concentrations (Bernhardt *et al.*, 2010).

Uptake and interactions in plants: Although the majority of studies on plant uptake and negative or positive effects of nanoparticles have been conducted on seed germination and root elongation in culture media (Peralta Videa *et al.*, 2011), they provide evidence that plant uptake of nanoparticles and response to the exposed nanoparticles are primarily dependant on the physicochemical properties of nanoparticles (e.g. composition, shape and size) and plant type (Ma *et al.*, 2010). In plant uptake processes, solutes translocated by diffusion or mass flow to the external surface of plant roots are taken up by movement across the cell wall and water-filled intercellular spaces of the root cortex (Marschner, 1995).

When nanomaterials are used in test systems, one has to be aware that some of the properties which need to be determined are largely dependent on the surrounding media and the temporal evolution of the nanomaterials. Thus, a primary focus should be to assess the nanomaterials in exactly the form/composition they have as manufactured, and in the formulation delivered to the end-user or the environment if the formulation contains free nanoparticles. Nanomaterials can exist as nanopowders; suspended in air (ultrafine particles, nanoparticles, aerosols), suspended in liquid (colloids) and incorporated in solids. For biological safety evaluation, manufactured nanomaterials need to be dispersed in an appropriate media. The interaction between these media and the nanomaterials can have a profound influence on the behaviour of the suspension.

5. SYNTHESIS OF NANOPARTICLES

Specific synthesis processes are employed to produce the various nanoparticles, coatings, dispersions or composites. Defined production and reaction conditions are crucial in obtaining such size-dependent particle features. Particle size, chemical composition, crystallinity and shape can be controlled by temperature, pH-value, concentration, chemical composition, surface modifications and process control. The top-down approach is essentially the breaking down of bulk material to get nano-sized particles. This can be achieved by using advanced techniques such as precision engineering and lithography which have been developed and optimized by industry during recent decades. Precision engineering supports the majority of the micro-electronics industry during the entire production process, and the high performance can be achieved through the use of a combination of improvements. These include the use of advanced nanostructure based on diamond or cubic boron nitride and sensors for size control, combined with numerical control and advanced servo-drive technologies. Lithography involves the patterning of a surface through exposure to light, ions or electrons, and the deposition of material on to that surface to produce the desired material. The bottom-up approach refers to the build-up of nanostructures from the bottom: atom-by-atom or molecule-by-molecule by physical and chemical methods which are in a nanoscale range (1 nm to 100 nm) using controlled manipulation of self-assembly of atoms and molecules. Chemical synthesis is a method of producing rough materials which can be used either directly in product in their bulk disordered form, or as the building blocks of more advanced ordered materials. Self-assembly is a bottom-up approach in which atoms or molecules organize themselves into ordered nanostructures by chemical-physical interactions between them. Positional assembly is the only technique in which single atoms, molecules or cluster can be positioned freely one-by-one.

Generally, top-down and bottom-up and different methods adopted to synthesized nanoparticles by using these techniques are summarized. In Drexler (1986) published the first book on nanotechnology “Engines of Creation: The Coming Era of Nanotechnology”, which led to the theory of “molecular engineering” becoming more popular. Drexler described the build-up of complex machines from individual atoms, which can independently manipulate molecules and atoms and thereby produces self-assembly nanostructures. Later on, in 1991, Drexler, Peterson and Pergamit published another book entitled “Unbounding the Future: The Nanotechnology Revolution” in which they use the terms “nanobots” or “assemblers” for nano processes in medicine applications and then the famous term “nanomedicine” was used for the first time after that.

6. DIFFERENT TYPES OF NANOPARTICLES

Nanoparticles can be classified into different types according to the size, morphology, physical and chemical properties. Some of them are carbon-based nanoparticles, ceramic nanoparticles, metal nanoparticles, semiconductor nanoparticles, polymeric nanoparticles and lipid-based nanoparticles. Nanoparticles types are commonly divided in two main groups: *organic* and *inorganic*. The first group includes micelles, dendrimers, liposomes, hybrid and compact polymeric nanoparticles. The second group includes fullerenes, quantum dots, silica and metal nanoparticles. Another way of classifying nanoparticles is based on their morphology, size and chemical properties. Based on physical and chemical characteristics, some of the important classes of nanoparticles are:

- **Carbon-based**-(fullerenes, carbon nanotubes, graphene, carbon dots). These materials are of great interest due to their electrical conductivity, high strength, structure, electron affinity, and versatility.
- **Metal**-They are purely made of the metal's precursors. Due to well-known localized surface plasmon resonance (LSPR) characteristics, these possess unique opto-electrical properties.
- **Ceramic**-These inorganic nonmetallic solids are getting great attention of researchers due to their use in applications such as catalysis, photocatalysis, photodegradation of dyes, and imaging applications.

- **Semiconductor** – Semiconductor materials possess properties between metals and non-metals and have wide bandgaps. Therefore, they are very important materials in photocatalysis, photo optics and electronic devices.
- **Polymers** – Scientists have developed many techniques to synthesize polymeric nanoparticles for a wide range of applications including surface coating, sensor technology, catalysis, and nanomedicine.
- **Lipids** – These NPs contain lipid moieties and are used in many biomedical applications as drug carriers. Lipid nanoparticles are also regarded as highly promising systems for delivering nucleic acids in gene therapy. So far nano products utilized in Agriculture viz.,
- **Cantilevers**: A cantilever is a beam anchored. Micro and nano cantilevers (MEMS / NEMS - devices), widely used in bio-sensing applications.
- **Nanopores** are formed by a pore-forming protein in a membrane such as a lipid bilayer (A hemolysin). Also formed in synthetic materials such as silicon nitride or graphene
- **Dendrimers** are highly branched, star-shaped macro molecules
- **Nanotubes**: Essentially 'tube' like structure, may be carbon / silicon / boron nitride. It is light weight but strong, used in electronics / construction / sensing
- **Quantum dots**: It is made of selenides or sulfides of metals, size varies from 2 to 10 nanometers in diameter, widely used for biomedical applications / sensor development
- **Nano shells** consist of an inner core of one type of material and an outer layer of another only a few nanometers thick, used as a smart delivery system

7. APPLICATION OF NANOTECHNOLOGY IN AGRICULTURE

- **Nano fertilizers**: Chemical fertilizers are limited in their application because of fertilizer loss which leads to environmental pollution and increases the cost of manufacturing (FAO, 2017). Around 40-70 percent N, 50-90 percent K and 80-90 percent P are dispersed in the ecosystem thus unavailable to the crop (Ombodi and Saigusa, 2000), and chemical interaction in soil causes 8–90 percent of standard phosphatic fertilizers to be lost and inaccessible to plants, resulting in long-term and economic losses. In this regard, nanotechnology has been used to lessen loss of nutrients, generate gradual fertilizer release, and increase nutrient distribution that aren't readily available. Nanotechnology has enabled researchers to examine nano range substances as fertilizer transporters or managed vectors for the development of smart fertilizers as emergent means to increase nutrient usage productivity and lowering pollution costs. Nanofertilizers can release nutrients, particularly $\text{NO}_3\text{-N}$, for up to 50 days, whereas urea-based fertilizers only release nutrients for 10-12 days. The nano fertilizer had 82 percent of N-use efficiency whereas the conventional fertilizer (urea) had a 42 percent N-use efficiency, resulting in increase in nitrogen-usage of 40 percent, which is impossible to obtain in the traditional system (Subramaniam *et al*, 2009).
- **Nano biosensors**: A biosensor is a tool that includes a biological recognition element with a physical or chemical detector to detect something. Wheat roots and rhizosphere microbes have been found to communicate with each other as a key component of chemical signalling networks (Monreal *et al*, 2015) *via* nanobiosensors.

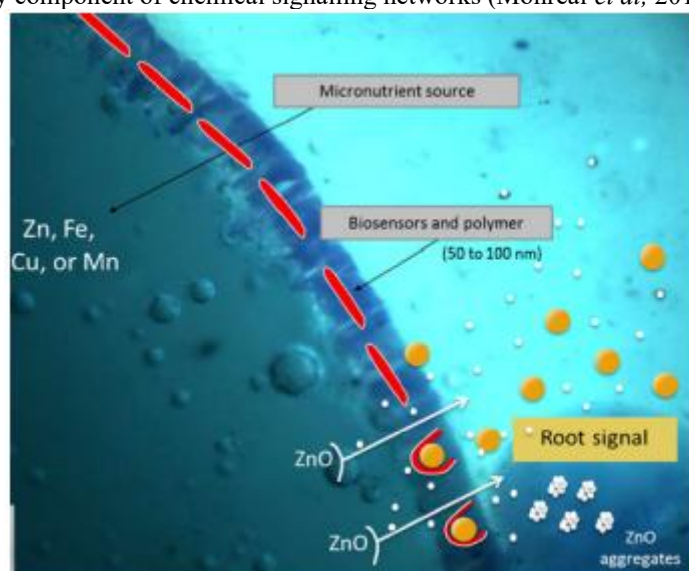


Figure.1 (yellow)-Specific root chemical signals that are bound to (red): a nanobiosensor placed in (blue): a polymer film coating (dark grey): ZnO-fertilizer nanoparticles (white spheres): the consequences of biosensor and signal binding process

- **Encapsulation**: Encapsulation reduces the solubility of active ingredients, runoff rates, and interactions with agricultural workers. Due to higher friction on the surface, nanomaterials coatings on fertilizer granules keeps the material in place with higher effectiveness than standard surfaces, allowing for more controlled release. De Rosa. (2010) suggested that nutrients may be encapsulated inside nanomaterials to create nano fertilizers. One of these novel facilities is the encapsulation of fertilizers in nanoparticles, which can be accomplished in three ways

i.e., Nutrients can be encased within nanosized substances, placed in polymer coatings and nanoparticles or emulsions are used to deliver the product.

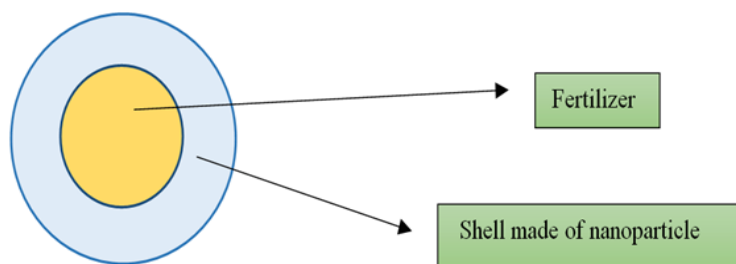


Figure 2. Encapsulation of fertilizer in nano-particulate polymeric shell.

Encapsulation allows targeted release of fertilizer. Fertilisers incorporated inside nanoparticles will boost nutrient uptake (Chinnamuthu and Boopathi, 2009). By placing and cementing fertiliser capsules, nano or sub nanocomposites could enable the gradual release of nutrients (Liu *et al.*, 2006) (Fig.2). It is claimed that a patented nanoparticle of N, P, K, micronutrients, and amino acids improves grain and crop nutrient uptake (Jinghua, 2004).

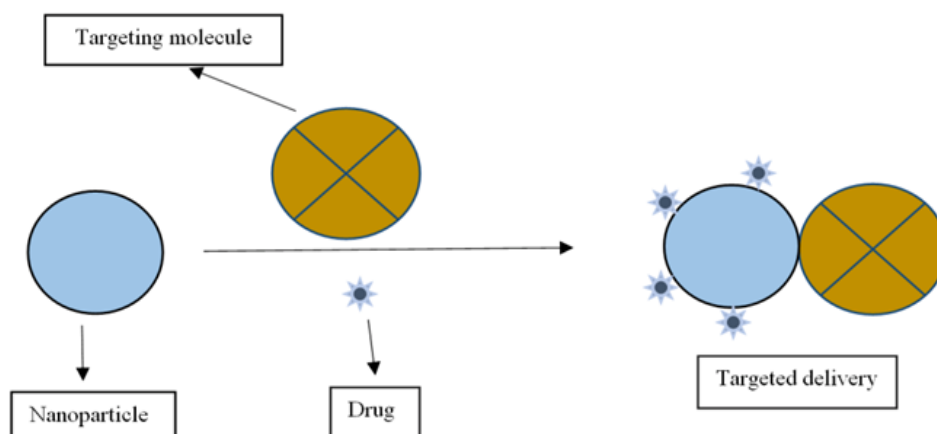


Figure:3 Targeted delivery of nano fertilizer.

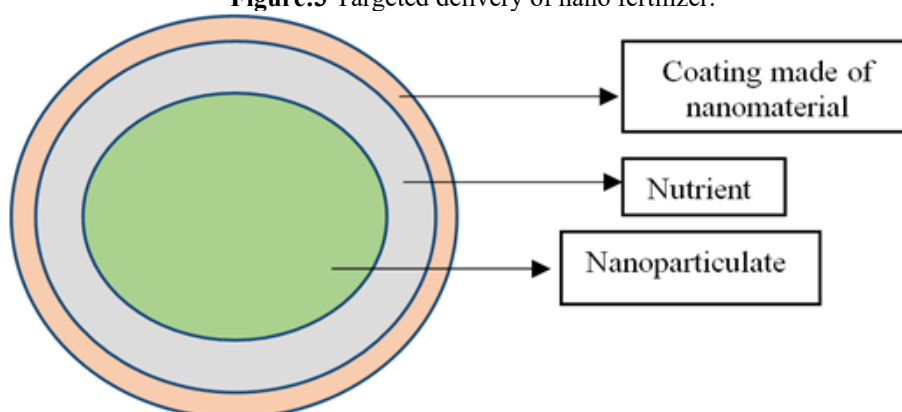


Figure:4 Fertilizer coated with nanoparticles for slow delivery of nutrient.

- **Nano herbicides:** Herbicides enclosed in polymeric core shell nanoparticles are nanoherbicides, which are alternate types of herbicides developed in conjunction with nanomaterials (Kumar *et al.*, 2015). Encapsulated target specific herbicides in nanoparticles are employed to eliminate specific weeds by acting on specific root receptors. The invention of a nanoparticle encapsulated target-specific herbicide chemical is focused at a particular binder of target weed roots, that penetrates the root system and is trans located to the portions that hinder glycolysis of the roots.
- **Nanotechnology and abiotic stresses:** Various nanoparticles used, have been proven beneficial on the growth and yield of crop by altering the physiological systems during drought of the crop. It has been found, for example, that foliar sprays of NPs of iron and oil per centage of safflower species can mitigate, negative effects in drought stress on parameters of yield thus yield can be enhanced. During drought conditions, the addition of NPs of titanium dioxide at the rate of 0.02 percent increased the plant height, ear number, biomass, ear weight, seed number, 1000 seed weight, harvest index and ultimate yield (starch and gluten content) (Jaberzadeh *et al.*, 2013). Therefore, these investigations revealed that the formulations enabling selected nanoparticles can favourably interact with probiotics of the plants that promotes drought tolerance and robust plant tissues.

- **Diagnosis and management of plant diseases:** The most challenging aspects of plant disease management is detecting the disease at the proper stage. Because a huge percentage of plant illnesses are only discovered at later stages, controlling them becomes a difficult effort. Recent research has found that nanoparticles can have antibacterial characteristics, which can be generated by either oxidative stress or bacterial cell wall physical breakdown caused by reactive oxygen species (ROS) generation (Gurunathan *et al.*, 2012).
- **Nanopesticides:** Nanoparticles can be effectively used in insect pest control and prevention of host infections. A new nano encapsulated pesticide formulation with better permeability solubility, stability and specificity is developed. Organic polymers mineral nanoparticles or surfactants of nanometer size are employed in the nano pesticidal development (Alfadul *et al.*, 2017). Insect-specific nano pesticides are going to be included in the new generation of pesticides while causing no harm to other critical soil insects (Kah *et al.*, 2013). Nontoxic and promising pesticide delivery technologies are being developed in order to increase crop output per unit of time while limiting negative consequences on ecosystem
- **Nanomaterials and genetic transformation:** NPs mediated transmittance has become extremely important in plant nano biotechnology. Nanoparticles can be used to facilitate genetic change in tissue cultures of plants. Nanoparticles are utilised in the isolation of protoplasm, for example, in reducing the impact of enzymes of the cell. Endocytosis is employed for the DNA delivery into the tobacco protoplast using mesoporous silica nanoparticles. Biolistic cannon also employed to deliver drugs, nanoparticles that are gold-coated and DNA to leaves and calluses (Torney *et al.*, 2007). In contrast to typical gold particles used with a gene gun, nanoparticles with gold coatings, transported DNA into *Nicotiana tabacum*, *Oryza sativa* and *Leucaena leucocephal* (Kumar *et al.*, 2010). Plasmid DNA that was Green-fluorescent protein (GFP)-encoded was efficiently transported into cells of turf-grass using poly (amidoamine) dendrimer nanoparticles (Pasupathy *et al.*, 2008).

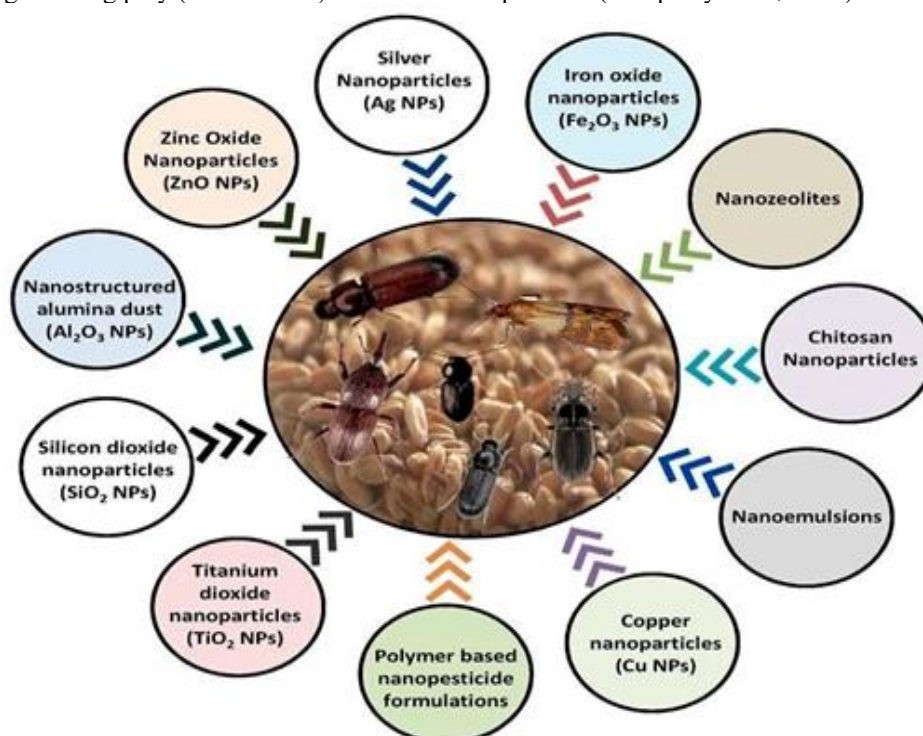


Fig.5: Overview of commonly used nanopesticide formulations

- **Nanoparticles for soil cleaning:** Several ways of using nanotechnology, particularly nanoparticles, used for cleaning the soil that are contaminated with heavy metals are being developed. Nanoclean-up procedure that involves introduction of iron nanoparticles within a contaminated area is developed. Nanoparticles flow along ground water and disinfect along the way, saving money over digging up the soil to decontaminate it. Activity of this nanoscale iron inside the soil is for 6-8 weeks, before dissolving in ground water or blending in with naturally occurring iron.

8. SEED SCIENCE IN NANO SCIENCE

Seed is nature's nano-gift to man. It is self-perpetuating biological entity that is able to survive in harsh environment on its own. Nanotechnology can be used to harness the full potential of seed. Seed production is a tedious process especially in wind pollinated crops. Detecting pollen load that will cause contamination is a sure method to ensure genetic purity. Pollen flight is determined by air temperature, humidity, wind velocity and pollen production of the crop. Use of bio nanosensors specific to contaminating pollen can help alert the possible contamination and thus reduces contamination. The same method can also be used to prevent pollen from Genetically modified crop from contaminating field crops and helps to fix isolation distance. Novel genes are being incorporated into seeds and sold in the market. Tracking of sold seeds could be done with the help of

nanobarcodes (Nicewarner Pena *et al.*, 2001) that are encodable, machine - readable, durable and sub-micron sized taggants. Disease spread through seeds and many times stored seeds are killed by pathogens. Nano-coating of seeds using elemental forms of Zn, Mn, Pa, Pt, Au, Ag will not only protect seeds but used in far less quantities than done today. Su and Li (2004) developed a technique known as quantum dots (QDs) as a fluorescence marker coupled with immuno-magnetic separation for E coli 0157:H7, which will be useful to separate unviable and infected seeds. Technologies such as encapsulation and controlled release methods have revolutionized the use of pesticides and herbicides. Seeds can also be imbibed with nano encapsulations with specific bacterial strain termed as Smart seed. It will thus reduce seed rate, ensure right field stand and improved crop performance. A smart seed can be programmed to germinate when adequate moisture is available that can be dispersed over a mountain range for reforestation (Natarajan and Sivasubramanian, 2008). Coating seeds with nano membrane, which senses the availability of water and allow seeds to imbibe only when time is right for germination, aerial broadcasting of seeds embedded with magnetic particle, detecting the moisture content during storage to take appropriate measure to reduce the damage and use of bioanalytical nanosensors to determine ageing of seeds are some possible thrust areas of research. A group of research workers is currently working on metal oxide nano-particles and carbon nanotube to improve the germination of rainfed crops. Khodakovskaya *et al.* (2009) have reported the use of carbon nanotube for improving the germination of tomato seeds through better permeation of moisture. Their data show that carbon nanotubes (CNTs) serve as new pores for water permeation by penetration of seed coat and act as a passage to channelize the water from the substrate into the seeds. These processes facilitate germination which can be exploited in rainfed agricultural system.

- **Detecting Contamination in Seed Field:** Seed production in wind-pollinated crops is an exceptionally tedious process due to the constant threat of airborne cross-pollination from undesirable sources. While traditional methods rely on time-consuming grow-out tests to assess genetic purity, directly detecting foreign pollen offers a foolproof way to safeguard crop integrity. To address this challenge, researchers at Michigan State University developed specialized crop-specific nano-sensors capable of instantly alerting seed farmers to foreign pollen presence via light or sound signals. This real-time detection allows farmers to accurately establish and fine-tune necessary isolation distances, ultimately enabling precise quantification of contaminants to guarantee ultimate seed purity.

- **Aerial Seeding:** Aerial seeding serves as a highly efficient method for large-scale afforestation by broadcasting tree seed mixtures over vast areas using aircraft. However, a persistent issue with standard aerial broadcasting is seed clustering, where multiple seeds fall in the exact same spot and compete for resources. To solve this, seeds are coated with varying sizes of magnetized iron nanoparticles, causing the seeds to magnetically repel one another once dropped. This magnetic repulsion ensures the seeds spread out evenly in mid-air, leading to well-distributed coverage across the terrain and faster, healthier forest establishment.

- **Hardening Seed - The Nanotechnological Way:** With over 60% of India's net sown area depending entirely on rainfed agriculture, farmers face severe challenges from unpredictable rainfall patterns. Standardized seed hardening techniques have been developed to enhance germination by helping seeds make the most of minimal available soil moisture. Seeds treated with these methods emerge significantly faster and demonstrate strong resilience against early-season droughts. Despite these valuable agronomic benefits, traditional seed hardening is rarely adopted by farmers due to operational and practical difficulties, opening a promising opportunity for nanotechnological innovations to simplify the process and make climate-resilient farming more accessible. Prasad *et al.* (2012) also observed that ZnO nanoparticles at a concentration of 1000 ppm improved the germination percentage, root growth, shoot growth, dry weight and pod yield in groundnut. In *Cicer arietinum*, Avinash *et al.* (2010) found that ZnO NPs increased the level of IAA in the roots (sprouts) and thereby an increase in the growth rate of plants. The beneficial effect of the ZnO NPs in improving the germination could be ascribed to higher precursor activity of nanoscale zinc in auxin production (Kobayashi and Mizutani, 1970). Apart from this, zinc is one of the essential nutrients required for plant growth. Being an important component of various enzymes that are responsible for driving many metabolic reactions in all crops. Zinc oxide NPs are reported to exhibit positive effect on the reactivity of phytohormones especially indole acetic acid (IAA) facilitating in phytostimulatory actions which dramatically regulates the plant growth. The improvement of Zn nutritional status also reduces the uptake of harmful heavy metals that hinders its toxicity in plants such as Cd (Adiloglu, 2002). Sahandi *et al.* (2011) tested four levels of nano silver (0, 20, 40, and 60 ppm) on medicinal (*Borago officinalis* L.) plant at growth stage and observed a raise in the concentration of nano silver from 20 ppm to 60 ppm leading to an improvement in the seed yield. Additionally, the lowest amount of seed yield was found with control plants. Increasing level of silver nitrate, the polyphenols compounds content was raised, but the enhancing level of nano silver resulting in the reduction of these components. Similar results were also reported by Mazumdar (2014) in rice.

- **Nano polymer coating:** Coating seeds with moisture sensitive nano polymer membrane that sense the availability of water and allow seeds to imbibe only when time is right for germination (45-50 % moisture availability). Groundnut is usually stored as pod testa is very thin and delicate and liable for mechanical damage and occupies more space mean while Insect and disease infestation, removal of shriveled and damaged seeds is not possible, seed certification, seed coat damage as inert matter and Nano Polymer Kernel coating solves the problem

- **Seed ageing:** Among the nanoparticles, ZnO (Li and Haneda *et al.*, 2003) and TiO₂ (Bhatkhande *et al.*, 2001) are best examples for photocatalysis properties. In the presence of UV light, the valency electron in the nanoparticles is excited to form electron hole pairs. The negative electrons are strong oxidizers. And the Zero Valent Iron is best electron donor (Karri *et al.*, 2005). Therefore, customizing the nanoparticles such as Zinc oxide (ZnO) and Zero Valent Iron (ZVI) to quench those free radicals that appear during seed deterioration and to increase the seed viability. Effect of Nano-TiO₂ on Strength of Naturally Aged Seeds and Growth of Spinach- The effects of nano-TiO₂ (rutile) and non-nano-TiO₂ on the germination and growth of naturally aged spinach seeds were studied by measuring the germination rate and vigor indexes of aged spinach seeds. An increase of these factors was observed at 0.25–4% nano-TiO₂ treatment. During the growth stage, the plant dry weight was increased, as was the chlorophyll formation, the ribulose biphosphate oxygenase activity, and the photosynthetic rate. The best results were found at 2.5% nano-TiO₂
- **Nano Sensors for Seed Storage:** Seeds during storage emit specific gases that reflect their degree of ageing and deterioration. By utilizing bio-analytical nanosensors and electronic noses (E-noses), these complex gas arrays can be detected and their odorant concentrations accurately estimated. This technology allows for the identification of volatile aldehydes, enabling operators to isolate seeds showing signs of deterioration and invigorate them prior to planting or use.
- **Seed Physiology:** Many seeds naturally exhibit dormancy, which is typically maintained by physiological inhibitors such as abscisic acid (ABA), dormin, and phenols. To overcome this barrier, nanotechnology enables seeds to be coated with specialized nanoparticles containing an array of bio-active chemicals. These nanoparticles penetrate the seed during the imbibition phase, effectively neutralizing the inhibitors and releasing dormancy to promote uniform and timely germination.
- **Genetically Modified Rice:** Advanced nanotechnology facilitates novel mutation breeding in rice through precision techniques like drilling nano-sized holes directly through the cell wall and injecting nitrogen into the nucleus to rearrange DNA and induce mutation. A notable application of this technique occurred in Thailand with the popular Khao-Kam variety at Chiang Mai University, where researchers successfully utilized nanotechnology to mutate the grain color from deep purple to white.
- **Nanoparticles based seed invigoration:** Nanopriming can be applied to seeds in order to provide protection for seeds during storage, improve germination, germination synchronization, and plant growth, as well as to increase the resistance of crops to abiotic or biotic stress conditions, which can help to reduce the required quantities of pesticides and fertilizers. Seed nanopriming also can be used for seed protection, as many nanoparticles have antimicrobial activities and also can load antimicrobial agents. In addition, nanopriming can be used aiming biofortification of seeds to promote an increase in food quality and production



Fig. 6: Comparative morphological, physiological, and structural observation of nano-primed seeds versus untreated controls.

Seed nano-priming is a new technology that uses nanomaterials, mainly nanoparticles, for seed priming. There is an important difference between seed priming and seed nano-priming, since conventional seed priming mainly employs water (hydropriming) or solutions containing substances (nutrients, hormones, or biopolymers) that adsorb on the seed and can result in seed coating (or dressing). In seed nanopriming, the media used are suspensions or nanoformulations, where the nanoparticles may or may not be taken up by the seeds. Even when

nanoparticle uptake occurs, the greatest fraction is retained on the seed surface as coating. Such seed coating can be used with fungicides or bactericides in order to protect against pathogens in the field or during storage. Different nanomaterials, including metallic, biogenic metallic, and polymeric nanoparticles, have also shown potential for seed nano-priming, resulting in the stimulation of plant growth and improvement in morphological and metabolic traits. This process can promote fast root and shoot development, with changes in the expression of genes that modulate metabolic processes, such as phytohormone production. Seed nanopriming changes the activity of the defence system, increasing the antioxidant levels and enzyme activities, so that the plants become more resistant to pests and other biotic and abiotic stresses under field conditions. Karimi *et al.* (2012) reported that wheat seeds nano coated with Ag NPs were able to protect seeds from fungus on par with a conventional fungicide namely carboxitiram and did not adversely affect the seeds ability to germinate, indicating Ag NPs might have fungicidal properties and could prevent deterioration of seeds due to pathogen infestation during storage (Jo and Kim 2009; Min 2009 and Nasrollahi *et al.*, 2011). Ag NPs exhibited the highest inhibition against *Aspergillus* species. In the present work, Ag NPs followed by ZnO NPs treated seeds had higher significant antibacterial activity against the fungi tested, viz. *A. flavus* and *Rhizoctonia solani*, than CuO and TiO₂ NPs used independently when compared to untreated seeds. The Ag NPs possessing antimicrobial activity were reported to be effective growth inhibitors against *Staphylococcus bacillus*, *Staphylococcus aureus* and *Pseudomonas aureginosa* (Ratan *et al.*, 2011). Padmavathi and Vijayaraghavan (2012) investigated the antibacterial activity of ZnO NPs with various particle sizes and found that increased antibacterial efficacy of ZnO NPs with decreasing particle size, opining abrasiveness and the surface oxygen species of ZnO NPs in promoting the biocidal properties. In one of the studies on groundnut seeds with nanoscale ZnO particles with a concentration of 1000 ppm also reported the significant increase in germination, shoot length, root length and vigor index (Prasad *et al.*, 2012). Another report showed that effect of ZnO nanoparticle on the seed germination and root growth in black gram (*Cicer arietinum*) seeds on the reactivity of phytohormones especially indole acetic acid (IAA) involved in the phytostimulatory actions. Due to oxygen vacancies, the oxygen deficient, i.e. zinc-rich ZnO nano particle increased the level of IAA in roots (sprouts) which in turn indicate the increase in the growth rate of plants (Avinash and Pandey *et al.*, 2010). Reports on mung (*Vigna radiate*) and in gram (*Cicer arietinum*) by using ZnO particle in agar method which found to affect the growth of mung and gram seedlings at different concentrations. The maximum effect was found at 20ppm for mung and 1ppm for gram (Pramod Mahajan *et al.*, 2011). Marimuthu (2007) in rice corroborate with the preset finding. reduction in glucose utilization occurs in the deteriorated seeds which are reflected through lower dehydrogenase and amylase activity. Thus, measured from the point of activity of these enzymes, NPs treated seeds were found to have higher enzymatic activity, showing the positive role of NPs in improving the seed vigour and viability. It is an established fact that, Zn and Fe are the important metal micronutrients that act as cofactors for the most of the enzyme complexes involved in respiration and food mobilization in seeds. The increased availability of these micronutrients at nanoscale with increased chemical reactivity resulted in the increase in synthesis and activity of the enzymes or could be due to repair of damaged vital cell organelles (Villiers, 1974; Villiers and Edgcumbe, 1975; Burgass and Powell, 1984) and counteraction of lipid peroxidation and minimization of free radical reactions. Most of the physiological parameters recorded and also the Zn content in the edible parts of crop plants in our study with nano Zn treatment either only seed / foliar treatment or seed priming with foliar application such as plant height, number of leaves, number of tillers, chlorophyll content, higher grain yield and higher biomass and higher Zn content in leaf, root, stem and seeds. Showed a significant positive response compared to the ZnSO₄ treatment. But all the Zn treated plants showed significantly affirmative response compared to the untreated control plants which explains the physiological importance of Zn in plant metabolism.

- **Carbon nano tube fast forward seed germination:** Research from the University of Arkansas demonstrates that carbon nanotubes (CNTs) can dramatically accelerate tomato seed germination by penetrating the seed coat and enhancing water absorption. While untreated control seeds showed no growth by the third day, seeds treated with CNTs achieved an average germination rate of 30% to 45%. Furthermore, the CNT-supplemented medium significantly boosted overall success over time, raising 12-day germination averages from 32% to between 74% and 82%, and reaching 90% by 20 days compared to 71% for the regular medium.
- **Food processing and packaging:** It acts as potent antimicrobial agent. Also traces the presence of contaminants, gases, microbes inside packaging (Rui *et al.*, 2016)
- **Nano Bio farming:** Green synthesized nanomaterials (utilization nanoparticles from vegetable wastes, fruit peel off, egg shells, weed plants and other agro-bio wastes) in modern organic agriculture, protected cultivation. Most effective for soil-less cultivation and also it protects environment.
- **Nano Hydro gel:** Hydro gel is made of sodium or potassium acrylate and is super absorbant which retains water. Controlled and uniform release of bio-active materials.
- **Nanotechnology:** As artificial intelligence and machine learning drive the next wave of mechanization and automation in modern agriculture, they are increasingly integrated with advanced nanotechnology to revolutionize crop production, monitoring, and management. This synergy encompasses Nano Biotechnology to enhance genetic and molecular traits, Nano Barcode Technology for precise tracking and traceability, and Nano Smart Delivery Systems in seeds (Smart Seeds) that optimize nutrient and agrochemical release. Furthermore, Nano Biosensors enable real-time environmental and crop monitoring, Nanotechnology in Plant Health Management ensures targeted disease and pest control, and innovations in Nanotechnology in Seed packaging

and Storage significantly extend shelf life and protect seed viability against adverse environmental conditions. The plant's reaction to environmental stress includes coordinated changes in water relations, photosynthetic pigments, antioxidant defense, osmolyte accumulation, and growth-related traits. Studies on wheat under combined salinity and heat stress have shown that these physiological and biochemical responses are linked to the differences in stress tolerance among wheat genotypes. This evidence offers a valuable physiological basis for determining the potential for enhancing plant resilience through the use of nano-enabled treatments, but the impact of nanoparticles needs to be evaluated on a case-by-case basis for each material, dose, crop, and stress scenario (Neelambari et al., 2024).

- **Seed moisture detection:** Simple and low-cost capacitive moisture sensor using a thin film of nanoparticles on electrodes. Sensing mechanism is proposed and the enhancement is based on the interaction of nanoparticles with the water vapor and the dielectric behavior. ZnO nanocomposites are for sensing moisture content of seeds - wheat (Singh *et al.*, 2018, Lee *et al.*, 2010).
- **Seed detection: DNA Barcoding:** Metallic nanoparticles were utilized for encoding seeds by constructed nanoscale electroplating of metal in desired pattern. Their specific traits or genic expressions for further usages. Widely used for marketing of national and international markets for tracking and controlling the movement of seeds. It includes all information like lot number, name of producer, variety details, parentages, date of seed testing and validity period (Azmat *et al.*, 2020, Harish M.S *et al.*, 2019).
- **Protection from Seed Borne Pathogens:** Nanoparticles may help in disruption of bacterial membranes and their hindrance by biofilm formation. Biofilms play an important part in development of bacterial resistance. NPs not only can combat bacterial and microbial resistance, but also act as a “medium and carrier” of antibiotics. Detecting Infections: Gold and silver nanoparticles were used widely (Mohamed A.K *et al.*, 2017, Sadak 2020)).
- **Disease Management:** SE-MgO nano composite in rice, Sepiolite, a magnesium silicate, was blended with MgO to form a (SE-MgO) nano composite that exhibited excellent antifungal activity against rice pathogens like *Fusarium verticillioides*, *Bipolaris oryzae*, *Fusarium fujikuroi* (Sidhu *et al.*, 2020, Ahmed et al., 2021)
- **Seed packing and handling:** Ligno-cellulosic nanomaterials used for development of light weight, highly durable and cost-effective packaging material for seeds. Bio and gas sensors also integrated with these packaging materials, they can also involve monitoring the changes in micro environment (AOSA, 1991, ISTA, 2021).
- **Biosafety on nanoparticles:** Utilization of green synthesized nanoparticles, rather than inorganic synthesized nanoparticles can reduce environmental threats. Through these problems of environment, plants, animals, and human beings can be minimize. It is less toxic, stable and sustainable for safer biological system.

9. MERITS AND DEMERITS OF NANOTECHNOLOGY

The applications of nanotechnology in modern agriculture are reported throughout the whole production chain, starting from the genetic level with the application of nanocarrier-assisted transformation systems that help in the development of genetically modified crops. Nano-priming treatments at the time of sowing condition seeds to germinate more uniformly and vigorously, while engineered carriers enable targeted feeding of nutrients and bioactive compounds, releasing them in step with crop demand rather than in a single wasteful dose. Protecting the standing crop also wins: nanoscale sensors and formulations enable early detection of pathogens and insect pests as well as precise, lower-volume delivery of control agents. The same sensing platforms are extended to quality assurance, detecting residues, toxins and adulterants at concentrations well below conventional analytical thresholds. Nanotechnological routes, beyond the field, add value to agricultural and agro-industrial residues, by converting biowaste into functional materials and inputs. Soil health is achieved through amendments that improve structure, moisture retention and nutrient availability in degraded land and the technology extends to systems that eliminate soil altogether, enabling hydroponic and other controlled environment production. These prospects are mitigated by constraints that go unaddressed. The synthesis of well characterized nanomaterials is still expensive and the cost is difficult to justify at field scale for low margin crops. More fundamentally, the fate of engineered nanoparticles in edible plants is poorly mapped; their accumulation in tissues, transfer along food chains and chemical transformation within biological systems are not systematically characterized, making it difficult to estimate long-term dietary exposure. Toxicity is strongly dependent on dose and exposures over the recommended limits have induced phytotoxic and cytotoxic responses in different test systems. Occupational exposure is a separate issue as metal nanoparticles in powdered or aerosolized form can be inhaled during manufacture, formulation and field application where respiratory deposition and subsequent systemic distribution are plausible. These gaps will need to be filled by harmonized toxicological testing and regulatory standards before the widespread deployment of this technology can be responsibly recommended.

10. CONCLUSION AND FUTURE PERSPECTIVES

Scientific community is exploring the potential application of nanotechnology in the field of Seed Science Research to tackle some of the most beleaguered areas. Utilization of nano products with their broad benefits *viz.*, Agro-biotechnological and genetic engineering tools, seed invigoration, seed encapsulation, nano composites-based moisture sensors for seed and soil, crop sensing, delivery systems, diagnosis and management of plant diseases and pests, for checking qualities of agricultural produces, maintenance of soil and water quality. Seed priming with zinc oxide nanoparticles @200 ppm improved seedling quality, photosynthetic

pigments and enzyme activities in maize. Seeds primed with silica nanoparticles @125 ppm recorded highest seedlings parameters and 175-200 ppm observed effective antimicrobial agent in rice. Seeds primed with titanium dioxide nanoparticles @60 ppm showed improved seedlings quality and biochemical characteristics in maize. Iron nano primed @2.0 ppm given significant effect on initial seedling quality in wheat. Nanoparticles influenced the growth of plants and in controlling surface microflora and insect pests. Concept of atomic engineering could enable DNA of seed to be rearranged in order to obtain different plant phenotypes including colour, growth season and yield Mechanical nano biosensors can be connected to user friendly devices through GPS can be effectively used for real time monitoring of contaminating pollen in seed production fields; such sensors can detect the contaminating pollen by its morphology and helps to take decision for corrective measures by seed grower. Optical or nano shell biosensors can be used for quick detection of seed quality in storage, such nano sensors known as electronic nose (E-nose). Which detects early release of gases like volatile aldehydes during seed ageing processes and further helps in scheduling of mid storage correction treatments Nanobiotechnology is still at its early stages of development the development is multi-directional and fast paced. Universities are forming nanotechnology centres and the number of papers and patent applications in the area is rising quickly. Realistically, some of these newly developed tools might not have viable Applications and could end-up on the 'technology shelf' in the future but offcourse there are definite benefits. Nanobiotechnology is interdisciplinary and brings together life scientists and Engineers. This, in turn, fuels further growth of ideas, which would not occur without these interdisciplinary interactions.

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