ISBN: 978-81-19149-15-5

10. Nanotechnology in Agriculture Against Climate Change

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Abstract:

Global agricultural production is facing substantial losses due to climate change-related phenomena's such cold, drought and salinity, which lead to tissue damage and that ultimately causes yield penalties. Ensuring food security is highly challenging in the developing countries by overcoming these climate change related phenomena. The development of novel and sustainable 'green' technologies is therefore becoming increasingly important. Nanotechnology provides invaluable opportunities to variety of industrial sectors. Recent focus has been driven to the development and optimization of nanomaterials for application in the agricultural sector towards improving growth, protection and overall performance of plants based on the small size, high surface to volume ratio and unique optical properties of nanomaterials. The present chapter provides a description and application of advanced nanoparticles and polymers at seed and plant level, covering biological, technical and socio-economical aspects of this promising approach. This technology offers an attractive alternative to established approaches in agriculture such as conventional breeding, genetic modification, fortification of agri-products and precision management of inputs with key advantages, representing a characteristic example of integrative plant physiology where multiple disciplines such as analytical chemistry, materials science and agriculture join hands to develop exciting new tools for modern agriculture against climate change.

Keywords:

Nanoparticles, Seed coatings, Nanomaterials, Biotechnology, Abiotic stress and Priming.

10.1 Introduction:

Agriculture is one of the most important sectors in world economy as it provides food and raw materials for variety of industries. The limit of natural resources such as arable land, soil, water and the growth of global population claim for agricultural progress must be efficient, viable and sustainable. Demographics will radically change over the coming future. World population is expected to increase and surpass 9.7 billion by 2050 and 11 billion by the year 2100 (United Nations, 2019). Projected growth in the world's population is likely to be concentrated in African and South Asian countries. Based on these, Food and Agricultural Organization (FAO) estimated that agriculture in 2050 should be able to produce food more than double to meet global demand (FAO, 2019). However, in most of the parts on the globe, further expansion of cultivable land is much limited. Especially in sub-Saharan Africa, Northern Africa and parts of Central Asia potential land expansion is constrained by water shortage and lack of infrastructure. Furthermore, in all these regions, agricultural land expansion could lead to further deforestation, which would destabilize ecosystem and its sustainability, because of the impact on greenhouse gas emissions and biodiversity loss and all these reversible accelerates climate change. Crop intensification can be a best alternative to land expansion. Although, by adopting this practice, soil does not have enough time to rejuvenate its fertility and productivity, thus leading to nutrient deficiencies and land degradation (Abhilash et al., 2016). In addition to the aforementioned issues, the changing climate poses a significant danger to agriculture and food security (Dubey et al., 2016). Changes in water availability, increasing frequency and intensity of extreme weather events, changes in rain and drought patterns, and increases in temperature and levels of carbon dioxide in the atmosphere all have a significant influence on the growth of agriculture (Zandalinas et al., 2018). One of the new ecological effects of climate change is undoubtedly the difficulties posed by abiotic stress on plant growth and development (Bellard et al., 2012). All research on abiotic environmental stressors or factors that can stress out a variety of species is included in the field of plant abiotic stress (He et al., 2018). These stressors include excessive sodium ions that cause salinity, extremely hot and low temperatures, light, radiation, and a lack of or surplus of water and vital nutrients. Combinations of these stresses commonly occur in the field, producing special consequences that cannot be predicted from the stressors alone (Suzuki et al., 2014), leading to unexpected physiological interactions. Different approaches are being used today to improve stress tolerance. Crop cultivars with varied stress-tolerant features have been bred during the past several decades with a lot of effort. This procedure has been conducted using two basic strategies. One involves breeding conventionally using methods like broad hybridization and mutation breeding. Despite their value to agriculture, these techniques are time-consuming and frequently produce unpredictably (Hu and Xiong, 2014). Another approach is to modify the genetic makeup of the plant by adding exogenous genes or altering the rate at which endogenous genes are expressed in order to increase stress tolerance (Hu and Xiong, 2014). In order to find and characterise the routes to build stress-tolerant agricultural plants, it is crucial to understand the molecular processes by which plants receive and transmit stress signals to cellular machinery to initiate adaptive responses (Kollist et al., 2019). Globally, the cultivation of genetically modified plants is restricted because this practise is now prohibited in many nations. While many nations continue to worry about detrimental effects on the environment, farmland, and biodiversity, parties to the Cartagena Protocol on Biosafety (Secretariat of the Convention on Biological Diversity, 2000) have the right to restrict or completely ban cultivation in their territories.

Priming is a fascinating alternate strategy for helping plants withstand environmental challenges. Through the efficient induction of already established defence pathways, chemical priming exhibits great promise for improving plant tolerance to these abiotic stresses without the need for genetic modifications. In comparison to unprimed plants, plants that have been pre-treated (or "primed") with specific natural or synthetic compounds respond better to less-than-ideal conditions (such as drought, heat, salinity, or heavy metals; Savvides et al., 2016).

Through the regulation of reactive oxygen species (ROS) accumulation, redox signalling, and gene expression that contributes to an enhanced stress response, priming enhances plant defence mechanisms by improving perception and/or amplification of signals (Balmer et al., 2015). Amino acids, phytohormones, metabolites with hormonal activity like polyamines, melatonin (Antoniou et al., 2017), reactive oxygen–nitrogen–sulfur species (Antoniou et al., 2016), fungicides (Filippou et al., 2016), as well as synthetic hybrid donors like NOSH aspirin (Antoniou et al., 2020). The concurrent use of nanotechnology and its tools beside with chemical priming will lowers the environmental burden (Khan et al., 2019). Nanoparticles, which range in size from 1 to 100 nm in at least one dimension (depicted in the **Figure 10.1** have a wide range of unique physicochemical characteristics. Due to their high surface energy and high surface-to-volume ratio, they exhibit higher reactivity, solubility, and biochemical activity (Dubchak et al., 2010). Various physical, chemical, and biological processes can produce nanoparticles, which have a variety of effects on plants by promoting their growth, productivity, and development (Singh et al., 2016b). Additionally, nanoparticles are crucial for shielding plants from a variety of abiotic stressors. In addition to protecting the photosynthetic machinery and enhancing photosynthesis by suppressing oxidative and osmotic stress, they have been demonstrated to scavenge ROS (Rico et al., 2013). Titanium oxide (TiO2), cerium dioxide (CeO2), zinc oxide (ZnO) and several other nanomaterials have all been put to the test in recent years to see whether they may help plants grow faster and handle stress better. It's interesting to note that some substances, especially when used at greater concentrations, might cause poisoning symptoms (Begum and Fugetsu, 2012; Gohari et al., 2020a). Due to oxidative stress brought on by nanoparticle exposure, crop yields, root and shoot length, and germination rate all suffer (Barhoumi et al., 2015).

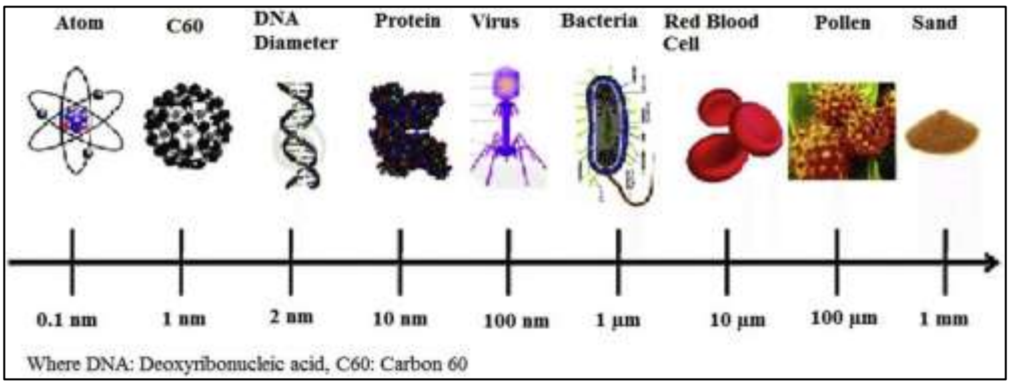

Figure 10.1: A pictorial exhibition of things in the "nano" (<100 nm) and "micro" (>100 nm) size ranges (DNA: Deoxyribonucleic acid, C60: Carbon 60).

Biological materials can also be used to create nanomaterials, in addition to chemical ones. Plant extracts can be used to biologically synthesise certain metallic nanoparticles since most plants contain sugars, enzymes, and phytochemicals such flavonoids, latex, phenolics, terpenoids, alcohols, amines, and hormones, among other things. In addition to producing products with well-defined size and form and reducing soil contamination, these substances act as stabilisers during eco-friendly nanoparticle synthesis methods (Dubchak et al., 2010; Singh et al., 2016a).

The use of nanomaterials to improved crop production and sustainable agriculture is still in its infancy. We anticipate that as our knowledge of nanotechnology grows, we will be able to take full use of its potential benefits. To construct "green" technology without harming the environment, it is vital to have a fundamental knowledge of how nanoparticles and sophisticated polymers interact with plants at the cellular and molecular level.

The parts that follow give a current account of the technical, biological, and socioeconomic aspects of contemporary nanotechnologies utilised in agricultural practises, with an emphasis on nanoparticles and sophisticated polymers used as seed coating agents.

10.2 Nanoparticles and Its Technical Aspects:

The word "Nano," which can be defined as 10^9 of any value or unit, was derived from the Greek word nanos, which meaning "dwarf." According to Ealias and Saravanakumar (2017), a group of substances, natural or artificial with at least one dimension less than 100 nm is referred to as nanoparticles.

Nowadays, nanotechnology is regarded as a very promising topic with a wide range of economic and scientific applications for creating innovative materials at the nanoscale. As demonstrated in **Figure 10.1** several types of nanoparticles have been identified based on the appearance and makeup of the particles.

In general, "Top down" and "Bottom up" techniques are used most frequently to synthesise nanoparticles **Figure 10.2**. When using "Top down" methods, different lithographic techniques like milling, grinding, and other methods are used to transform bulk materials into substances at the nanoscale. The "Bottom up" technique, in contrast, uses physical and chemical processes to create nanomaterials by atoms self-assembling into new nuclei and then growing into particles with nano-scales (Kulkarni, 2014a, b).

It should be mentioned that the majority of these technologies rely on intricate processes, and frequently, they need the use of severe conditions, including high temperatures and poisonous starting materials, which not only raises operating expenses but also increases minor hazardous contamination on finished goods.

Many attempts have been made to use biological catalysts (such as plants, bacteria, fungi, and yeasts) as an environmentally friendly approach in the synthesis of nanoparticles in order to overcome these obstacles (Singh et al., 2016a). The structures of the nanomaterials are characterised using a variety of methods. The most popular methods in this area are spectroscopy and microscopy techniques.

10.3 Application of Nanomaterials in Agricultural Industry to Mitigate Climate Change:

Application of nanomaterials in agricultural industries in order to increase productivity of lands and crops, especially under suboptimal situations, started at the beginning of the 21th century (Duhan et al., 2017; He et al., 2019).

Nevertheless, agricultural science's understanding of nanotechnology is still limited. Numerous nanomaterials have been developed with the potential to revolutionise the agricultural sector. These materials have both benefits and drawbacks.

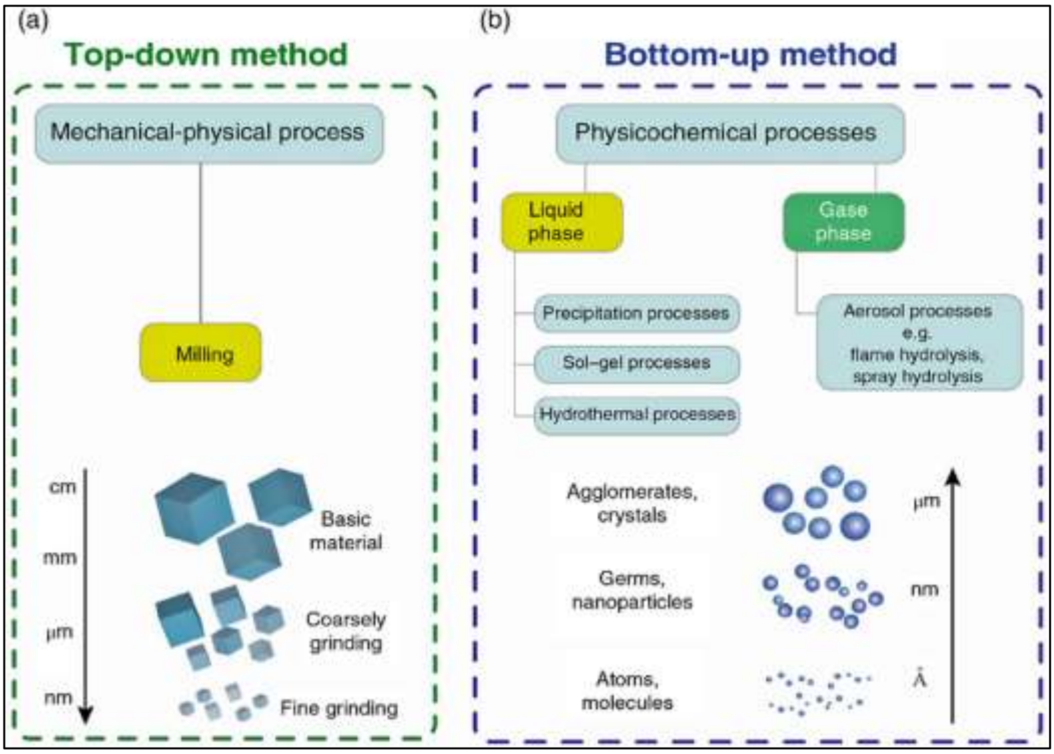

Figure 10.2: Schematic of the (a) top-down and (b) bottom-up approaches for making nanoparticles. Adapted from Roohinejad and Greiner (2017) with permission copyright © 2017 John Wiley and Sons.

In addition to addressing a variety of agricultural issues (such as the detection of pollutants, issues with soil structure, plant disease, pests and pathogens, delivery of pesticides, fertilisers and nutrients, and delivery of genetic materials), they frequently improve food quality and safety, crop growth, and environmental conditions monitoring (Siddiqui et al., 2015; Solanki et al., 2015; He et al., 2019). In the agricultural industry, a variety of nanomaterials are employed, including single-walled carbon nanotubes (SWCNTs), multi-walled carbon nanotubes (MWCNTs), graphene oxide (GO), silver (Ag), iron (Fe), silicon (Si), zinc (Zn), zinc oxide (ZnO), and titanium dioxide (TiO2) (Duhan et al., 2017; He et al., 2019).

As a result, methods of this promising methodology include controlled release, site-specific fertiliser delivery, being carriers for a variety of essential compounds, protection against pathogens and diseases, improved nutrient absorption, and increased efficiency of pesticides, fungicides, and herbicides, leading to enhanced plant growth (Kashyap et al., 2015; Solanki et al., 2015; Abobatta, 2018a; He et al., 2019).

Since they can be used in almost every aspect of the agriculture industry, including production, processing, storage, and transportation (Duhan et al., 2017), nanomaterials increase efficiency, productivity, and agricultural protection and production (Khot et al., 2012). Due to their size, high surface area, precise dosage, slow release, and other unique properties, nanomaterials generally enhance various practises in plant and crop protection, nutrition, and management as shown in the **Figure 10.3**. As a result, food quality and safety are improved, and agricultural inputs are reduced (Prasad et al., 2017).

The key benefits of this technology are the slow and controlled release of nanomaterials with a reduced dosage of the primary component (He et al., 2019). Additionally, nanoscale materials enhance soil structure and health and increase plant tolerance to a variety of environmental factors like drought, salinity, and temperature (Kah et al., 2019).

A. Nanofertilizers: As was already noted, there are several uses for nanomaterials in agriculture. Improved fertiliser delivery (Duhan et al., 2017; Abobatta, 2018a) leads to higher nutrient absorption by plant cells and reduced nutrient loss (Solanki et al., 2015), which is the first and most important function. They synchronise the administration of macro- and micronutrients (Kah et al., 2019). According to (Solanki et al., 2015) and (Siddiqui et al., 2015), major components of chemical fertilisers (N, P, and K) are not accessible to plants, which results in repeated fertiliser treatments with nutritional imbalance, environmental contamination, a decline in soil microflora, and a deficit of nitrogen fixation. The wide surface areas, targeted delivery methods, gradual and controlled release in response to environmental cues and biological demands of nanostructured fertilisers boost the efficacy of nutrient usage. The absorption, translocation, and destiny of nano fertilizers are determined by plant species, age, growing environment, physiological characteristic, functionalization stability, and the manner of distribution of nanomaterials (Solanki et al., 2015). Indeed, due to their persistent release, nanoparticles with encapsulated fertilisers increase agricultural productivity (Duhan et al., 2017).

Due to their special physicochemical characteristics, such as high reactivity, compatible pore size, particle morphology (Solanki et al., 2015; Siddiqui et al., 2015; Abobatta, 2018a), and the ability to penetrate cells and deliver themselves immediately inside organisms, they allow for cultivation on poor land. By boosting seed germination, seedling growth, photosynthetic activity, nitrogen metabolism, carbohydrate and protein synthesis, and reducing environmental side effects, nanofertilizers ultimately improve plant growth and yield (Solanki et al., 2015; Taha, 2016). The penetration of nanomaterials into seeds is the primary factor for improved seed germination (Khot et al., 2012). Nanofertilizers include nano-phosphorous (P), nano-Fe, nano-Mg, and nano-Zn. Furthermore, due to their competitive mechanical, electrical, thermal, and chemical properties, carbon nanotubes (CNTs) could be used as nutrient carriers for macro- and micro-nutrients to reduce their applied quantities with encouraging results in agriculture (Taha, 2016).

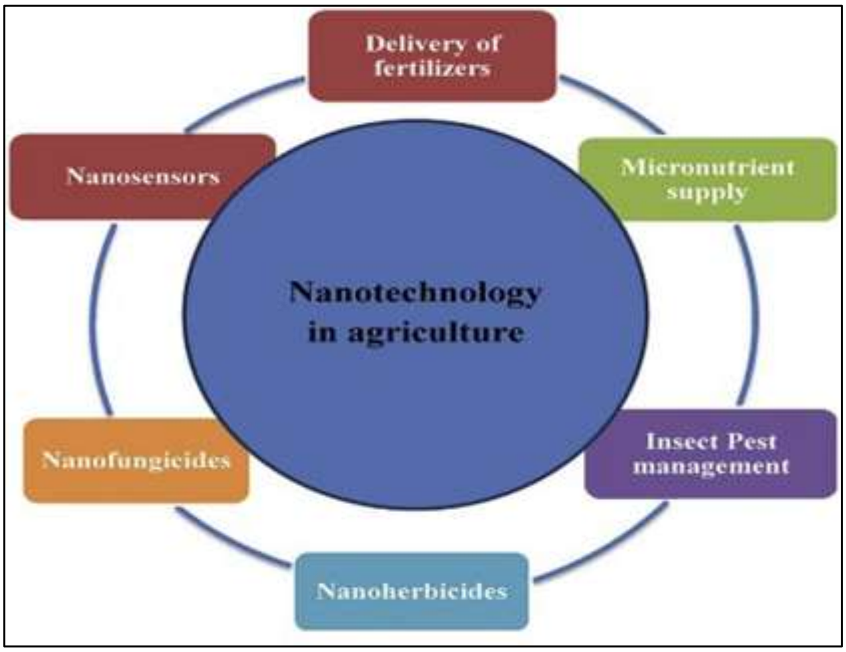

Figure 10.3: Schematic Representation of Applications of Nanotechnology in Agriculture.

B. Nanopesticides: Nano pesticides are used to control insects and pests. Due to the active and delayed release of active compounds (such as Ag, TiO2, ZnO, and Al2O3), some nanoparticles have a strong potential to manage and control pests (Duhan et al., 2017). This makes them an affordable and trustworthy alternative to synthetic pesticides that have negative side effects. Due to their high surface area and improved affinity to their target, nano pesticides reduce organic solvent runoff and unintended pesticide movement. Nano formulations also achieve faster soil degradation and slower plant degradation, with residue levels in foodstuffs that are below regulatory standards (Duhan et al., 2017). In addition, nanoparticles might serve as smart field systems and quick diagnostic instruments for pathogen identification, detecting diseases in crops and notifying producers to apply the necessary materials before the development of symptoms (Khot et al., 2012; Kah et al., 2019).

C. Nanofungicides: Chemical fungicides harm plants and pose risks to human health and the environment. Depending on the size and structure of the nanoparticles, nano fungicides offer beneficial answers to these issues. In terms of antifungal activity, silver (Ag), titanium dioxide (TiO2), and zinc oxide (ZnO) nanoparticles have the most potential (Duhan et al., 2017). Due to their large surface area and surface fraction, Ag nanoparticles are the most often used nano fungicides due to their antibacterial capabilities (He et al., 2019). Ag NPs deactivate the thiol groups in the cell walls of fungi, resulting in transmembrane damage, fungal DNA mutation, and dissociation of the respiratory chain enzyme complexes, which decreases membrane permeability and results in cell lysis (Duhan et al., 2017). While TiO2 NPs have photocatalytic and antibacterial properties that help to protect plants, ZnO NPs also exhibit antimicrobial, antibacterial, and antifungal activities (Duhan et al., 2017)

D. Nanoherbicides: Application of Nano herbicides is an environmentally benign and leaves no toxic leftovers in the soil or environment. According to Duhan et al. (2017), chemical herbicides, particularly those that get numerous applications, harm plants, impair soil fertility, contaminate the soil, and create weed resistance. Therefore, using nanomaterials to create nano herbicide formulations has the potential to address the aforementioned shortcomings (Chaudhry et al., 2018). Examples of such methods are showed that nanoencapsulation enhances the herbicidal activity of atrazine against mustard plants as evidenced by decreased net photosynthesis and PSII maximum quantum yield, and the work by Kumar et al. (2017), which demonstrated that herbicide-loaded pectin nanoparticles are more cytotoxic to Chenopodium album plants.

E. Nanosensors: Nanosensors (Duhan et al., 2017), which have been widely used in the agriculture industry due to their potential for environmental monitoring of pollution in soil and aquifers (Prasad et al., 2017), represent the last use. According to (Chaudhry et al. 2018), nanosensors might be used to swiftly and precisely assess the health of the soil, crops, and diagnose plant illnesses. In order to identify the presence of *Xanthomonas axonopodis pv. vesicatoria*, a plant pathogen that causes bacterial spot infections in solanaceous crops, fluorescent silica nanoparticles coupled with antibody molecules have been utilised. As a sensor, gold nanoparticles are used the most frequently (He et al., 2019). Due to their high sensitivity, low detection limits, super selectivity, quick reactions, and tiny size, smart nanomaterials might also be employed as nanosensors to detect pesticide residues (Khot et al., 2012). The recent creation of a nanosensor platform for the detection of hazardous Cd^{2+} and acetylcholinesterase (AChE) activity in actual water samples is a pertinent example (Fang et al., 2017).

10.4 Role of Nanomaterials to Mitigate Environmental Stresses:

In response to various abiotic stress conditions, plants experience ROS build up and oxidative damage as major growth inhibitors that significantly reduce crop output. The restriction of CO2 fixation and suppression of ROS scavenging by enzymatic and non-enzymatic processes in biological systems are the most significant effects of abiotic stressors on plants (Wu et al., 2017). Application of nanomaterials has been shown to promote plant growth and development in both stress-free and normal environments Table 10.1. When plants are exposed to abiotic stimuli including salt, drought, heat, and heavy metals, they immediately produce ROS, which severely damages the organelles, structures, and functions of the cells. Plants have evolved a sophisticated antioxidant system that includes both non-enzymatic (such as carotenoids, tocopherols, ascorbate, and glutathione) and enzymatic (such as SOD, CAT, and APX) antioxidants to protect against this damage (Gill and Tuteja, 2010) and was pictorially depicted in figure 11.4. In order to protect plants from stressful situations, nanomaterials activate these defense systems (Kim et al., 2017; Kumaraswamy et al., 2018). According to Kah et al. (2019), the principal protective mechanism of nanomaterials is connected to the enhanced activity, availability, or dissolution of materials as a function of nanoscale size. It is important to remember that every nanomaterial has a unique mode of action and unique mechanism to help plants become tolerant to environmental shocks or even to normal circumstances. However, protective effects of nanomaterials are typically attributed to their small size and high permeability to plant cells that interrupt stressful factors (Wu et al., 2017).

The precise general mechanism of protection has not yet been fully elucidated. The section that follows looks at prominent instances of nanoparticles utilised as stress-relieving chemicals.

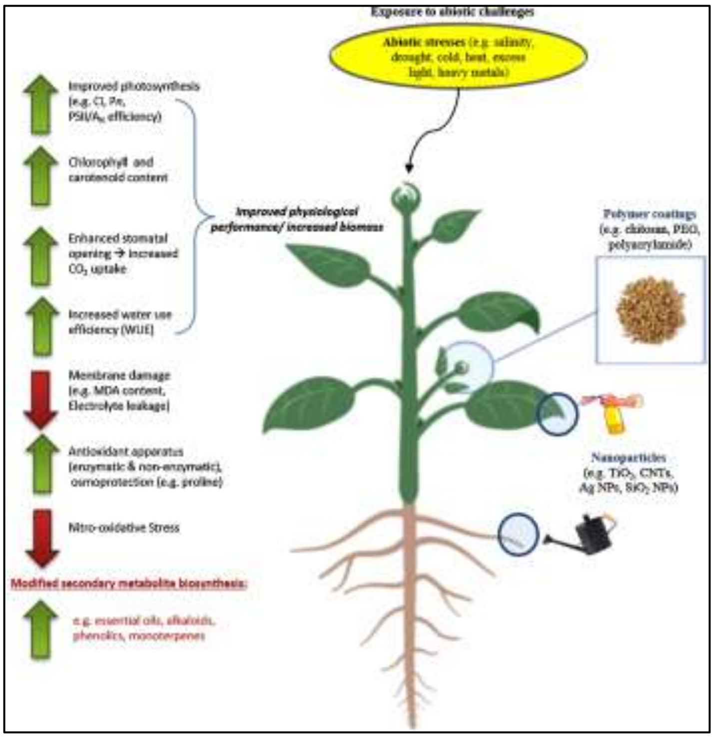

Figure 10.4: Model illustrating concept of nanomaterial application in plants and seeds and resulting alterations in physiological and biochemical parameters.

10.5 Nano Materials in The Form of Polymer Coatings as Seed Priming:

As a result of their uncontrolled release into the environment, agrochemicals used in their free, unprotected form have significant negative effects on both the environment and the economy (Mukhopadhyay, 2014), necessitate frequent application to plants and crops, and may have harmful effects on human health (Nicolopoulou-Stamati et al., 2016). In recent years, seed priming methods have paid a lot of attention to polymer coatings (Taylor et al., 1998; Scott, 1998; Sharma et al., 2015).

Biocompatible and biodegradable polymers, in particular, have been utilised as seed coverings to enable the encapsulation and prolonged release of nutrients, growth regulators, and pesticides used against diseases, pests, insects, etc. involved in seed germination, root, and shoot development processes. In addition, the application of polymer coatings in seed priming may improve the ability of plants and crops to withstand abiotic stresses such as heat, salt, drought, and heavy metals (Pitman and Läuchli., 2002). Because agriculture is one of the industries that uses the most water globally, this has a positive effect on crop yield while lowering water demand in the industry (Pfister et al., 2011). Pelleting, encrusting, and film coating are the three primary sub-categories of seed coating techniques.

Table 10.1: Effect of Nanoparticle Application in Plants Growing Under Different Abiotic Stress Conditions.

Nanoparticle	Concentration	Abiotic stress	Plant species	Effects
CeO2 (Rico *et al*., 2013)	62.5, 125, 250, and 500 mg L−1	oxidative stress	*Oryza sativa*	Decreased membrane damage and photosynthetic stress in shoots
Poly (acrylic acid) coated nanoceria (PNC) (Wu *et al*., 2018)	50 mg/L i	Salinity stress	*Arabidopsis thaliana*	Improved photosynthetic performance and biomass
CuO NPs (Lalau *et al*., 2015)	0.1–10 g/L	Non-stress	*Landoltia punctate*	Increased total carotenoid contents, induction of bleaching and pigmentation
Chitosan-PVA + Cu NPs (Hernandez-Hernandez *et al*., 2018)	50, 100, 150 mg L−1	Salinity stress	*Solanum lycopersicum*	Increased vitamin C and lycopene content, enhanced tolerance to salinity stress
Ag NPs (Karami-Mehrian *et al*., 2015)	0, 25, 50, 75 and 100 mg L−1	Oxidative stress	*Solanum lycopersicum*	Increased production of all amino acids except methionine and tryptophan, increased SOD, CAT and POX enzymatic activities

Nanoparticle	Concentration	Abiotic stress	Plant species	Effects
Ag NPs (Iqbal *et al*., 2019)	25, 50, 75 and 100 mg/l	Heat stress	*Triticum aestivum*	Increased leaf area, leaf number, leaf fresh weight and leaf dry weight
Anionic Cerium Oxide (Wu *et al*., 2017)	50 mg/L	Light and heat and chilling stress	*Arabidopsis thaliana*	Increased photosynthetic capacity
TiO2 NPs (Mohammadi *et al*., 2014)	2–10 mg/L	Cold stress	*Cicer arietimun*	Enhanced stability of chlorophyll and carotenoid content during cold stress.
Silicon nanoparticles (Tripathi *et al*., 2015)	10 μM	chromium (VI) toxicity	*Pisum sativum*	Reduced Cr accumulation and oxidative stress, increased nutrient uptake

10.6 Conclusion:

Nanotechnology is an innovative strategy with significant promise for use in improving plant nutrition, development, and defence against harsh environmental factors. As a sustainable method with less agricultural hazards, this may be accomplished by using nanoparticles and/or sophisticated polymers in plant and seed tissue. These are multi-billion-dollar industries, but they encounter obstacles in entering the market, primarily due to the high cost of manufacturing nanotechnology products, which are needed in large quantities in the agricultural sector. The 'green' sustainable product is supported by a number of papers, and the field is seeing an increase in interest.

However, there are still a lot of unanswered questions regarding our understanding of the uptake potential and the ecotoxicity of various nanomaterials, and their mode of operation is still not completely understood. Therefore, more study is needed using interdisciplinary strategies (systems biology, toxicology, analytical chemistry) to understand how nanomaterials interact with biological macromolecules found in environments and crops, allowing for further development of this fascinating technology.

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