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Plant resilience nanotechnological approaches to mitigate climate change and biotic and abiotic stress

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Abstract

A robust and sustainable agricultural production system is necessary to fulfill the world's food needs. Growing population pressures and drastic climatic fluctuations have rendered traditional chemical-based farming methods useless. Recent studies have shown that nanotechnology has enormous potential for sustainable crop production. Use of nanotechnology in effectiveness of pest, editing of genome with full efficiency and the application of plant sensors. Unfathomable mechanical perceptions into the possible uses of concocted nanomaterials designed for increased crop stress flexibility and production are provided by this review. We have also talked about how technologically ready nano-based techniques are to paint a clear picture of our existing understanding of the topic. To create research goals that support a sustainable agri-tech revolution enabled by nanotechnology, the current obstacles is to the upscaling of nano-biotechnology in production of crop, end to end with the supervisory necessities to allay associated hazards and enable community suitability. In summary, this analysis has illustrated the value of nano-enabled methods for enhancing crop health and their potential to mitigate global food security issues. In agriculture, nanotechnology a rapidly developing area to study is essential for encouraging improvements in plant productivity, chlorophyll content, and gene expression. Nanoparticles improve drought tolerance by increasing root hydraulic conductivity and water uptake and displaying a distinct array of proteins complex in stress signaling, oxidoreduction, and the elimination of reactive oxygen species (ROS). The nutrients are easily transferred to every area of the plant because nanoparticles are very mobile by nature. Therefore, the primary motivation for authoring this chapter is to identify strategies for employing nano preparations to boost plant's potential under stressful circumstances.

Keywords: Agriculture, abiotic stress, nanotechnology, stress resilience, nano-sensors

1. Introduction

Production of food and delivery system are under incredible strain owed to a number of aspects, together with soil contamination, population increase, water limitations, and fast climate change (Usman and Farooq 2020) ^[73]. Food security is the most important issue of the century because of the increasing complexity of the problem caused by the reduction of arable land owing to industrialization and urbanisation. To fulfil the global food demands a more productive and stress-resistant system is required. Technical advances are still required for crop production to continue, despite the fact that it has substantially improved since the green revolution (Husaini *et al.*, 2023) ^[23]. Furthermore, the wasteful use of agrochemicals puts sustainable agricultural methods at risk production. Because of their low nutrient effectiveness, greater dangers to the environment, increased production costs and declining farmer profitability, synthetic fertilisers are bad for plant sustainability (Ahmed *et al.*, 2023) ^[3]. It is true that over time, traditional breeding techniques have greatly improved crop productivity and agricultural features. But because of techniques like backcrossing, pure line selection, and single seed descent, these procedures might take a long time, and they might have trouble transferring new features between species, which can impede the quick growth of improved variants (S. K. Jat and Bhattacharya 2020) ^[26]. Furthermore, the necessity for modern agricultural practices to change in order to discourse conservational issues and maintain long-term ecological equilibrium is becoming increasingly apparent. Nanotechnology has been combined by numerous precise arenas to generate innovative goods and know-hows to progress crop plant attributes (Fraceto *et al.*, 2016) ^[19].

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Numerous applications of nanotechnology in agriculture, after seed sprouting to post-harvesting, will improve crop productivity and quality (Singh and Sharma 2021) ^[66]. Concocted nanomaterials, or ENMs (engineered nonmaterial's) are the vital component of the agri-tech revolution. By bypassing biological barriers, these materials' <100 nm nanoscale size permits them to effectively disperse foliar or root treatments that deliver nutrients and chemicals. Furthermore, environmental contaminants and heavy metals in soil media can be detected using NM-based optical and electrochemical sensors. This shift can be facilitated by ENMs, which can be employed as sensors in plants. This allows for extensive crop health monitoring at both high temporal and spatial resolution (Giraldo *et al.*, 2019) ^[20]. The mechanical and physio-chemical features of ENMs could be altered over manufacturing to change their mode of action and delivery path, enabling the release and intelligent distribution of the active components to the desired place (M. Kah and Tufenkji 2019) ^[29]. The capabilities of genome editing technology have been greatly enhanced by CRISPR. Its low intracellular transport efficiency, which

drastically reduces the success rate, is the biggest barrier to its application in genome alteration. When paired with polymers, liposomes, and inorganic nanoparticles, certain ENMs have shown remarkable effectiveness in gene transfer (S. K. Jat and Bhattacharya 2020) ^[26], these ENMs are non-viral nano transporters. Nanotechnology also contributes to the reduction of preharvest food waste by delivering nutrients and chemicals in a targeted manner that lead to more effective resource utilisation as well as improved stress and disease control. ENMs are a viable option for sustainable agriculture because of the aforementioned characteristics (Noman and Ahmed 2023) ^[3]. The primary objective of this assessment is to gain a deeper information of the possible uses of nanotechnology-enabled methods to increase stress tolerance. These techniques include smart micronutrient delivery, smart plant genome editing, smart nano sensors, and limitations on the field-scale application of ENMs. This overview aids in understanding how ENMs function as a system to improve crop efficiency and preserve the environment. (Fig 1)

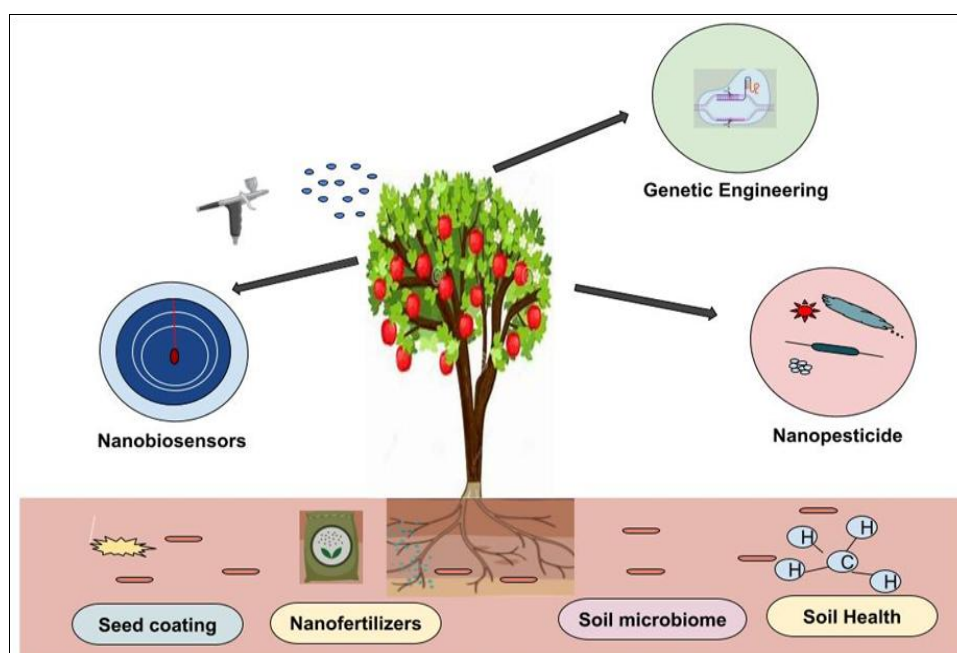


Fig 1: Potential application of ENM (engineered nanomaterials) in sustainable agriculture.

2. Nanotechnology and agriculture

The field of study referred to as "nano-pesticides, nano-fertilizers" provides novel approaches for creating distinct, nanoscale-sized active chemicals, as well as information about their composition and dispersion. In order to accomplish these goals, technology is quickly becoming into a very fascinating area of study. Pesticides are used in cultivation to control insects and herbal diseases. In order to mitigate the problems associated with traditional insecticides, a novel field of study known as technology has generated pesticides that exhibit higher efficacy with less active ingredient content. The conveyer molecule or essential component in pesticides has a relatively high external area to capacity relation, which offers them unique and exploitable advantages (Yasur and Rani 2013) ^[83]. Formulations like nano-emulsions, nanosuspensions, nanogels, and metal compound-based pesticides are made for different action and applications. The promising benefit is that the particles are smaller than typical insecticides, which helps to distribute the ingredients more evenly on insect surfaces. Every day, there is

more freedom to use particles as fertilisers, insecticides, and nano-delivery systems because of their greater efficiency and lower dose needs. However, humans and other animals may also be impacted by the nano-entities during or after the application. How these artificial nano-entities interact with biological systems is mostly unclear at this time.

Thus, in order to make the change viable a more thorough understanding of their interactions and any drawbacks is also necessary prior to their extensive application in crop protection and production. Many species, including fungi, nematodes, plants, bacteria, and other microbes, are used to make biopesticides. The main advantages of employing natural compounds called biopesticides rather than conventional pesticides are listed below.

Benefits of pharmacological formulations usually consist of:

- Scaling solubility of essential components that are insoluble in water
- Minimal exposure, virtually no environmental problems

- Extremely potent in minute quantities,
- Just affect the particular pest and organisms that are closely related.
- enhanced stability of formulation
- Substitution of toxic organic solvents with non-conventional pesticides
- The capacity to progressively release active ingredients
- Enhanced stability to prevent degeneration too soon
- Decreased particle size leads to increased insecticidal action and improved mobility.
- Greater surface area could lengthen their lives.

3. Applications of ENMs

ENMs have a wide range of uses, including coating materials for seeds, acting as nano-biosensors, acting as nano-fertilizers to enhance soil microbiota and health, acting as nano-pesticides to effectively manage pathogens, and acting as nanocarriers to support crop genetic engineering. These cutting-edge nanotechnology-based approaches have the power to completely transform farming methods and advance the creation of resilient and sustainable food production systems. Additionally, by delivering nutrients in a targeted manner, developing cost-effective resource recovery plans, turning plants into smart sensors that can anticipate impending stress, genetically modifying plants to create more resilient cultivars and managing crops better to prevent crop losses, are all possible benefits of ENMs (Pal and Kaur 2023) [53].

These techniques can deliver higher results by minimising collateral environmental damage and utilising less resources. lists the many nano-enabled crop improvement methods, underlying challenges, and possible outcomes.

3.1. Nonfertilizer effective way to use agrochemicals

Nano-based approaches have the capacity to growth of plants through improved fertilisation through targeted nutrient delivery for efficient utilisation, progressive nutrient release, and direct uptake of nanoscale nutrients (Rehman *et al.* 2022) [60]. Heavy metal nanoparticles are used in nano fertilizers due to their special qualities and possible advantages in promoting plant development and nutrient uptake, rather than solely to satisfy the nutritional requirements of plants. While synthetic nanoparticles come in a variety of forms, AuNPs and Ag NPs are the most widely utilised since they are simple to prepare, readily conjugated, and provide encouraging outcomes in a range of experimental scenarios (Kanwar *et al.*, 2019) [30]. It has been possible to create NPs that are specifically suited to the requirements of different plant-related activities by using metal oxides (Al_2O_3 , SiO_2 , TiO_2 , CeO_2 , Fe_2O_4 , etc.) and metals (Zn, Ag, Cu, Fe, Au, and Ni). It has been observed that applying nanoscale iron to rice and maize greatly increases germination, chlorophyll content, and other physiological parameters (Perna and Govindaraju 2021) [56]. (Larue *et al.* 2018) [40] investigated whether the optimal concentration of TiNPs sprayed on leaves may enhance the plant's capacity for photosynthesis as well as other physiological processes. Zinc nanoparticles (ZnNPs) have been shown to greatly promote seed germination in a wide range of crops, including soybeans, wheat, onions, and peanuts (Faizan *et al.*, 2020) [10]. Plants treated with graphene oxide had shorter seminal roots but also more adventitious roots. Garlic and coriander plants showed improved leaf, stem, root, flower, and fruit growth when exposed to graphene quantum dots, which were synthesised by (Chakravarty *et al.*, 2015) [11]. Nanomaterials can help lessen the amount lost to infiltration and runoff by

releasing fertilisers gradually. However, associated to macronutrients, the administration of nanoscale micronutrients has less of an effect.

3.2. Nano pesticides: Improve plant pathogen control

In order to guarantee the long-term cultivation of crops, it is essential to minimise crop sufferers instigated by numerous diseases, pests, and ecological strains. Nanotechnology-enabled pesticides could assistance with these initiatives. Based on estimations, the worldwide pesticide market is projected to increase to US\$ billion by 2023 from US\$ billion in 2013, (Singh and Mazumdar 2022) [67]. There is a 0.1% probability that insecticides sprayed in the field will wind up where they are supposed to (Sabzevari *et al.*, 2022) [61] the targeted application of pesticides can be aided by nano-formulations, which could further expand this accurateness. The suppression of plant pathogenic fungi, including *Magnaporthe grisea* (rice blast) and *Bipolaris sorokiniana* (common root rot), has been reported (Kim *et al.*, 2009) [37]. The NP treatment suggestively decreased the fungal invasion. The operative attentions of Ag NPs required to reduce colonisation by 50% (EC50) for *B. sorokiniana* were greater than those required for *M. grisea*. Although results of the aforementioned studies suggest that Ag NPs can reduce some diseases, they varied and were dependent on the type and concentration of AgNPs employed. For certain crops to develop resistance, chitosan is essential. demonstrated the effect of bio-functionalized MnNPs in suppressing Fusarium wilt disease in watermelon by interfering with Fon infection, inducing host defence mechanisms, and modifying the soil microbial population. When watermelon roots and shoots were treated with 100 $\mu\text{g mL}^{-1}$ of bio-MnNPs, the Mn concentration rose, promoting better progress and suppressing Fusarium wilt by blocking the Fe on contamination method. Controlling fungal attacks requires the supply of insecticides tailored to the exact site. In order to regulate *M. grisea*, (Kim *et al.*, 2012) [37], suggested an enzyme-responsive β -glucanase nano delivery to modify the amount of chlorothalonil (CHT) in the plant vascular structure. This would synthesise CHT@MSNs- β -glucans by attaching β -glucans from the pore rims to the yeast cell walls of MSNs. At this point, nano-pesticides are ready for usage and offer a practical means of achieving sustainable crop production. To describe the new materials' sophistication, including selectivity and lack of sensitivity to environmental stimuli, more investigation is required. While there are no such issues with currently available products like Kocide 3000, there are obstacles to infield delivery of nanomaterials, such as the potential for in-tank pressurisation to change the structure of nano-formulations. These factors must be carefully evaluated and managed as such. In agriculture, nanomaterials are being investigated for controlled release, targeted distribution, and increased pesticide efficiency.

To guarantee sustainable and safe usage while minimising adverse impacts on human health, ecosystems and plants, extensive research and risk assessment are necessary. This is because there is concern about the ability for plants to absorb nano-pesticides and the ensuing effects on plant health and food safety. In agriculture, nanomaterials are being investigated for controlled release, targeted distribution, and increased pesticide efficiency. To guarantee sustainable and safe usage while minimising adverse impacts on human health, ecosystems, and plants, extensive research and risk assessment are necessary. This is because there is concern about the ability for plants to absorb nano-pesticides and the ensuing effects on plant health and food safety.

3.3. Nano sensors: Enhance precision agriculture

Agricultural automation has shown to be beneficial in that it requires less labour and ensures effective crop management while also being environmentally friendly. Plant protection and sustainability can be ensured by farmers communicating with the plants through the use of plant nano sensors (Khandelwal and Joshi 2019) ^[36] Magnaporthe grise36a. Plant-integrated nanoparticles can convert specialised signalling molecules linked to nutrient deficits and stress into electrical or optical signals that can be detected by sensor devices. The automated evaluation of plant health, stress levels, and nutritional balance is achieved through the use of nano-based devices such as global positioning systems, global navigation satellite systems, and nano-biosensors. This has made it possible to oversee several agricultural projects alone without the need for personal inspections (Srivastava *et al.*, 2017; Tshabalala *et al.*, 2022) ^[69, 71]. Plant health is monitored in real time, which facilitates effective resource management before the loss and significantly increases growth and survival. It has cleared the path for sustainable agriculture, which will have more control over the management of resources, the health of the soil, crop enhancement through genetic engineering, and the strategic use of agrochemicals like fertilisers (Bartolucci and Scognamiglio 2022) ^[8]. In order to identify, monitor, and combat pathogen infections in plants, nano-sensors have emerged as a crucial instrument. They are accomplished of identifying a broad variety of targets, counting as diseases, fertilisers, pesticides, herbicides, insecticides, soil pH, moisture, etc. The produced information supports guard crops from dangerous illnesses and increase productivity by offering the soil with the exact nutrients (Peng and Zhang 2022) ^[54]. The right use of nano-sensors can improve agricultural productivity while also making farming easier for farmers. Precision farming, which will turn traditional farming into clever, cost-effective, and sustainable farming, is making progress in the right direction with this (Muthumalai *et al.*, 2022).

3.4. Nanocarriers: Efficient biomolecule delivery

Nanotechnology allows for the stabilisation of genetic materials such as DNA, in adding to transferring heritable knowledge to enhance gene editing in plants, dsRNA to boost its effectiveness as a pesticide. The development of cutting-edge genetic engineering methods like CRISPR-Cas9 has greatly expanded the possible for increasing crop resilience and productivity. Though, applying such techniques in plant biotechnology still presents a challenge: getting foreign material entering the plant cell through the cell wall. When it comes to the grafting and embattled distribution of desirable exogenic proteins for genome excision, nanomaterials can be extremely important (Wang and Grandio 2019) ^[78]. In contrast, DNA plasmids coding for CRISPR can be introduced into plants in place of foreign DNA, resulting in regulated Cas9 expression through a non-biostic and non-pathogenic mechanism. (Ishii *et al.*, 2022; Landry and Mitter 2019) ^[25, 39]. Conversely, very few studies have examined the transport of nanoparticles crossways shrub cell walls. Plant physiology is affected by artificial nanoparticles, and there are techniques to modify their size, shape, tensile strength and aspect ratio, and other physical and chemical features of these nanomaterials influences their ability to internalise plant cells need further study.

4. Mechanism by nanotechnology

Resilience of the ecosystem and food security, and sustainable agricultural production are all greatly enhanced by the

application of nanotechnology in agriculture. Carbon dots (CDs), which have special qualities including programmable photoluminescence, biocompatibility, and minimal toxicity, are one important nanomaterial in this area. Because of their exceptional biocompatibility, CDs are safe to use in agricultural settings. Because of their capacity to boost photosynthesis and enhance solar energy utilisation, which raises crop output, they have the potential to be growth enhancers. Moreover, the hydrophilicity of CDs speeds up plant water absorption and seed germination, which promotes plant growth (Wang *et al.*, 2022) ^[76].

By reducing biotic and abiotic stressors, their antioxidant and antibacterial qualities also improve plant health. Additionally, CDs are used in agricultural sensors to support the development of smart sensors by facilitating the detection of pesticides and herbicides. Furthermore, horticulture can benefit from nanotechnology, which increases fruit and vegetable quality, production, and shelf life. For improving crop growth, fertility, and disease monitoring, tailored and effective solutions are offered by nano pesticides, nano fertilizers, and nano devices (Rana *et al.*, 2021) ^[58]. The function of polyamines (PAs) as essential bio-stimulants for plant development and strain tolerance is another fascinating topic. Gaining insight into the molecular intricacy of PAs signalling can aid in boosting agricultural yield and stress tolerance in plants (Tyagi *et al.*, 2022) ^[72].

Furthermore, when zinc oxide nanoparticles (n-ZnO) are applied topically to lucerne under heat stress, it can better prevent superior plant development. This suggests that applying n-ZnO via foliar application beforehand is a more a practical method to reduce environmental dangers associated with nanoparticle transfer while shielding lucerne from the damaging effects of heat stress (Kareem and Hassan 2022) ^[31]. The antibacterial characteristics these metal-based nanoparticles have a great deal of promise for stopping fungus and bacteria that cause plant disease, another area in which nanotechnology shows considerable promise (Li and Zhang *et al.*, 2023) ^[42]. By triggering tolerance mechanisms, such as the overexpression of OsCNGC6 and the upregulation of NHX1, LEA and P5CS, three Ca²⁺ signalling proteins, *Fritillaria imperialis* (Crown imperial) effectively survives freezing stress. (Hajhashemi and Brestic 2020) ^[21]. Further, carbonaceous nanomaterials (CNMs) in particular have made it possible for flesh rejuvenation in biomedical claims (Mamidi *et al.*, 2022) ^[46]. In order to improve global food security, nano pesticides provide a more effective and environmentally friendly method of controlling pests. Nevertheless, future research is required to comprehend the negative results of various nano pesticides. The claim of nanotechnology to agriculture is a game-changing strategy that has broad advantages for raising output, resilience to changing conditions, and quality (Wang *et al.*, 2022) ^[76].

4.1. Promotion of plant development

The agricultural industry suffers significant financial losses as outcome of ecological conditions such as heat, drought, frost, and salinity. Due to an intensification in the incidence and strength of pressures that are more dangerous to the production of sustainably produced crops, weather alteration is consuming a significant influence on crop productivity (Vema and Sudheer 2022) ^[74]. In command to control the properties of environmental stressors and enhance plant development and photosynthetic efficiency, a variety of nanomaterials have been employed (Shalaby and Bayoumi 2022) ^[64]. Plant photosynthetic efficiency has been shown to be improved by cerium oxide

nanoparticles (NPs) through the reduction of responsive oxygen type buildup during stressful conditions (Wu and Shabala 2018)^[82]. There is insufficient data to determine the degree of technological readiness of the agrochemical industry in relation to nano-based seed coating strategies. It is also challenging to evaluate the benefits of the technology in a complete manner because the advantages are not consistently disclosed. Recent research indicates that coatings made of biosynthesized AgNPs (Mahakham and Sarmah 2017)^[45] and the electro spun method of cobalt NPs has the probable to improve sprouting effectiveness. The usage of zinc as ZnO provides a consequence on physiological parameters and tobacco callus growth than other forms of zinc. They accumulate more zinc when administered to the callus as NMs. This resulted in increased protein levels in addition to promoting callus development (Mazaheri-Tirani and Dayani 2020; Wiszniewska *et al.*, 2021)^[47, 80].

To increase amounts of TSS (total soluble protein), phosphorus, and chlorophyll in the beans and wheat, ZnO NPs were sprayed foliar and this will rise the Zn content and growth performance when compared to the routinely utilised zinc supplements. (Elhaj Baddar *et al.*, 2018)^[17]. Furthermore, it has been found that nanomaterials are very successful in accelerating and enhancing seed sprouting as well as raising the capacity for reproduction in plants (Wu, H., and Li, Z 2022).

4.2. Modification of plant microbiome

By maximising water retention, boosting nutrient uptake, and guarding against nanomaterials may be able to treat plant illnesses, soil properties and raise agricultural output and sustainability (da Silva Júnior *et al.*, 2021)^[14]. The significance of plant-microbe interaction is widely acknowledged in agriculture. The control of soil and Phyto-microbiome resulted in improved resistance to saline irrigation fluids and helped to suppress illnesses (Jayaraman *et al.*, 2021; Qin and Druzhinina 2016)^[27]. Research has documented how the microbial community in the soil may be altered by nanomaterials like CuO, Ag, and TiO₂, which in turn controls important aspects of the soil and plants. It include substantial modifications to plant metabolic systems, enhanced fruit and grain yield, and increased biomass. These nanomaterials also exhibit promise in enhancing the production of biomolecules, including those with possible medical uses, plant growth, seed germination, and photosynthetic efficiency. Under stress, multiwalled A variety of plant species benefit from the promotion effects of carbon nanotubes and graphene-based nanomaterials, which lessen the negative impacts of salinity and drought. They have also been employed as antifungal agents by encasing pesticides in them. For this reason, it is important to carefully consider how these materials affect plant growth, development, and disease prevention in the rhizosphere (Wagay and Singh 2019)^[75].

4.3. Enhancement of soil quality

Enhancing the quality of food and agricultural yield can be greatly benefited by improved soil, especially in regions where environmental pressures and soil degradation are already present. Conventional methods for conditioning soil on agricultural land do not primarily rely on nanotechnology (Wang *et al.*, 2021)^[78]. Nonetheless, a variety of nanomaterials are available for use in soil conditioning (Al-Mamun and Hasan 2021; Das *et al.*, 2021)^[5, 15]. Furthermore, (Liu *et al.*, 2017) examined the activities of the potassium-rich feldspar-derived hydrothermally created nano-based mineral soil conditioner, which included raising soil pH, improving soil density and

lowering crop toxicity from aluminium and cadmium. Furthermore, claim that the use of biodegradable cross-linkers increased the capacity to retain water. Chitosan nanoparticles (NPs) have the potential to improve soil properties and increase wheat crop output (El-Abdeen *et al.*, 2019)^[16]. Unfortunately, there aren't any estimates or feasibility analyses to construct these nano-based conditioners for field-scale claims, and the majority of research in this sector is done at the lab size. As traditional methods have been used for decades to improve soil characteristics, it is difficult to replace them with nanomaterials because of the high amount needed and lack of opportunities in precision agriculture (Or *et al.*, 2021). Since the technology is still in its initial stages, further feasibility testing will be required earlier any progress is made.

5. Nanotechnology in abiotic stressors

Abiotic stress management and plant adaptation are in high demand due to multiple abiotic challenges and the ongoing global increase in climate change (Wani *et al.*, 2016)^[79]. The numerous ways that plants respond to abiotic challenges and maintain their growth must be highly significant. A response that has emerged in response to the acknowledged adaptations of plants to abiotic challenges is the use of nanomaterials (Hatami *et al.*, 2016; Reddy *et al.*, 2016; Khan *et al.*, 2017)^[22, 59, 34]. Usage of nanodevices are depending on the growth stages included beneficial and harmful impacts on the development of plant. Nanotechnology includes special nanomaterial assets that make agricultural investigate on crop enhancement and stress reduction easier. Rapid advancements in nanotechnology have validated metal-based nanoparticles, extending from 1 to 100 nm in size, as alternative plant mineral nutrition and stimulants in minuscule quantities. By reviewing relevant research and their own work, (Khan *et al.* 2017)^[34] assumed that nanoparticles could help plants adapt and tolerate stress by promoting protection systems and stress-associated gene appearance. In response to external stressors, plants activate a variety of transcellular membrane sensors, mostly through the use of Ca₂⁺ channels and Ca₂⁺ binding proteins (Thapa *et al.* 2011)^[70]. Subsequent downstream mechanisms lead to modifications in the expression levels of genes, which ultimately result in the ability of plants to adapt to stress. The application of nanoparticles enhances plant responses to drought stress when compared to conventional bulk fertilizer (Saxena *et al.* 2016)^[62]. For instance, ZnO nanoparticle spray increased the percentage of soybean seeds that germinated when they were under water stress (Sedghi *et al.*, 2013)^[63]. Similarly, adding ZnO nanoparticles to the soil greatly increased sorghum productivity and nitrogen uptake (Dimkpa and Singh 2019)^[10]. Although the probable role of nanoparticles in enhancing shrub defense mechanisms against abiotic stress, including aquatic stress, has been thoroughly examined, there are still a number of unanswered questions. Researchers (Askary *et al.*, 2017; Choudhary *et al.*, 2017; Iqbal *et al.*, 2019; Pérez-Labrada *et al.*, 2019)^[6, 12, 24, 55] have conclusively confirmed the effect of metal-based nanoparticles on increasing numerous plant species ability to adapt to different abiotic stressors. It is yet unknown how they contribute to believable gene expression during stressful circumstances.

5.1. Effects of nanoparticles on abiotic stress in plants

Abiotic stress include heat, drought, salt and heavy metal toxicity/deficiency compromise the growth and productivity of most agriculture plant species. Due to this, they evolve a defense mechanism to fend off these pressures on several levels by using

molecular, biochemical, and physiological regulatory pathways. To properly regulate the modification of gene expressions in order to cope with these strains, plants follow different molecular pathways. Numerous researches have shown that the effect of nanoparticles on growth and development of the plants depends on their amount. According to (Laware and Raskar 2014) ^[41], Nanoparticles also improve SOD, CAT and POD, three antioxidant enzymes. The way that plants respond to abiotic stress involves intricate modifications to their morphology, metabolism, and biology. A variety of methods, including genetically engineering plant types with unique genetic organizations that enable improved performance under stress, have been used to increase the tolerance of plants against abiotic stress. The application of nanoparticles has enhanced germination and seedling growth rate, demonstrating that their application in plants lead to crop improvement, in addition to certain physiological activities like nitrogen metabolism, carbohydrate contents, protein and a range of positive alterations in gene expression. It is now clear that materials with nanostructures can increase a plant's resistance to water stress by improving its water intake, root hydraulic conductance, and differential mobility, which allows nutrients to reach nearly every area of the plant quickly. The ways in which different nanomaterials might alleviate the main abiotic stresses that crop plants face, including temperature, salinity, flooding, drought, and heavy metal stress

The drought is one of the main abiotic factors that negatively affects crop productivity and plant development among other abiotic stresses. Many strategies are used in plants to deal with this drought stress, but the use of nanoparticles is believed to be the most effective and capable. (Linh *et al.* 2020) ^[43] examined the responses of soyabean crop plants subjected to zinc oxide, iron, copper and cobalt oxide nanoparticles during a drought. The outcomes of the experiment demonstrated that these metal-based nanoparticles help exposed plants tolerate drought. Similarly, (Song and Jiang 2012) ^[68] informed that the application of 5 mg/l concentration of silver nanoparticles, with a particle size of around 6 nm, activated the antioxidant system and increased the action of superoxide, dismutase, catalase, and peroxidase in the *Spirodela polyrhiza* plant.

When gold nanoparticles were applied to *Brassica juncea* seedlings, the plants levels of proline and hydrogen peroxide increased along with the activity of antioxidant enzymes such as glutathione reductase, catalase, guaiacol peroxidase and peroxidase. Playing silver nanoparticles to *Brassica juncea* increased the activity of antioxidant enzymes such catalase, guaiacol peroxidase and ascorbate peroxidase, which in turn reduced the quantity of reactive oxygen species (ROS) (Sharma *et al.*, 2012) ^[65]

5.2. Use of nanotechnology in biotic stress

Biotic stressors, which have a detrimental impact on crop output as well as plant shape, include pathogen infection and herbivore attack. These are important agricultural restrictions. As a physiological, ecological, and genetic unit, plants live in a variety of situations that are either beneficial, neutral, or harmful to them. The occurrence of these dangerous bacteria, insects, pests, and herbivores, respectively, causes biotic stressors. They seriously harm the health and functionality of plants. In addition to having a detrimental impact on food quality, recurring biotic stressors brought on by shifting environmental patterns also result in pre- and post-harvest crop losses. The (FAO) of the United Nations reports that weeds, phytopathogenic organisms, and pest incidence cause 20–40% of crop production losses.

(Mitra *et al.*, 2021) ^[48].

Plants experience a range of reactions when biotic stressors such as pests, weeds, insects, and disease invasion occur. Pathogenic organisms and plants can interact to change physiological responses and regulate the metabolism if carbohydrate. (Berger *et al.*, 2007) ^[9]. They have an impact on how plants metabolize and produce characteristics as a result. In either case, the increased occurrence of biotic is stressors stimulated by the regularly shifting climate conditions. However, there is little information available to us on output losses brought on by pathogen infection. One of the most promising methods for preserving plant health and guaranteeing food security is nanotechnology. According to (Khan *et al.* 2019) ^[33], nanotechnology is a transdisciplinary and interdisciplinary field of study that works with particles with sizes ranging from 0.1 to 100 nanometers. When it comes to boosting crop yield and productivity, nanotechnology is a cutting-edge technique that offers greater benefits than traditional approaches. According to (Khan *et al.*, 2021 and Banerjee *et al.*, 2016) ^[35, 7], the nanomaterials improve gene expression, soil health, crop development, stress tolerance, seed germination, and ecological sustainability. Additionally, plant nanobiotechnology is utilized to give plants disease resistance and reduce their responses to biotic stress. In agricultural systems, improvement techniques of crops have all been made possible by nano sensors and nano biosensors. (Kerry *et al.* 2017) ^[32]. Numerous management strategies form the foundation of our farming system. Crop management has become more challenging due to weeds, insect pests, and plant diseases, which has forced the creation of creative solutions to lower biotic stresses and, eventually, crop losses. Agrochemicals are widely used in the agricultural system to manage phytopathogens, as is well known. Since synthetic chemicals are harmful to social health, the ecology and plants, crop production gains from the application of nanotechnology to disease control. The application of nano formulations for crop protection and productivity has grown dramatically in the last several years. Nano pesticides, nano fungicides, and nano fertilizers are a few of them. The optimum concentration of these NPs guarantees environmental sustainability while also reducing plant diseases. They have antibacterial properties. Many crop species use silver nanoparticles (NPs) because of their fungicidal and antibacterial qualities (Kim *et al.*, 2012) ^[37]. According to (Abdelmalek and Salaheldin 2016) ^[1], AgNPs have antifungal effects against *Penicillium digitatum*.

5.2.1. Mechanism of nanaoparticles in biotic stress environment

Nanoparticles (NPs) are minuscule particles that are essential to the growth and metabolic processes of plant systems. As previously mentioned, after being absorbed by plant roots or other components, NPs go via a number of cell organelles. It typically comprises the vascular tissues' apoplastic and symplastic routes. A thorough examination of the several processes behind nanoparticles mode of action in response to biotic stresses is required. Silver, nanoparticles cause harm to nucleic acid by penetrating bacterial and fungal cells. According to research by (Kumari *et al.*, 2017) ^[38], Ag NPs directly inhibit *A. solani*, reducing its spore count and preventing the establishment of infection, hence mitigating its harmful effects. Ag NPs killed fungal spores by altering their permeability and respiration and demonstrated direct attachment to *F. oxysporum* (Abkhoo and Panjehkeh, 2017) ^[2]. Fungal hyphae are plasmolyzed by AgNPs. According to (Ahmed *et al.*, 2020) ^[4], AgNPs made with *Bacillus cereus* SZT1 reduce cellular ROS

and boost antioxidant enzymes to inhibit the leaf blight pathogen. According to (Chun *et al.*, 2018) ^[13], chitosan nanoparticles improve tomato susceptibility to Fusarium and *Iyazi* by upregulating the genes for chitinases, β -1,3-glucanase, and antioxidant enzymes.

6. Nanoparticles uptake, synthesis and characterization

NPs are gradually being absorbed from the earth, atmosphere, water, etc. It passes through a number of bio-geo-transformations that establish its availability within the plant. (Fig 2) After being taken up by the roots, the NPs are moved to various parts of the cells. Research suggests that it may frequently advance concurrently with cellular penetration of nutrients and water (Mukherjee *et al.* 2016) ^[49]. Size, surface

charge, segregation, type of plant, growing circumstances and surroundings all have a significant impact on its bioaccumulation and adsorption, which is essential for its passage through different cell organelles and tissues. In ryegrass, ZnO NP absorption is being investigated. Small-sized NPs can reach plant roots directly through the epidermis, by capillary forces, or through osmotic pressure. The size of the NPs affects their ability to enter the cell membrane. They enter the circulatory system through the cell wall and proceed apoplastically. When NPs are transferred to the circulatory system via the casparian strip, they exhibit simplistic mobility. Binding to carrier proteins found in the membrane of endodermal cells, pore creation, and transport comprise further movement.

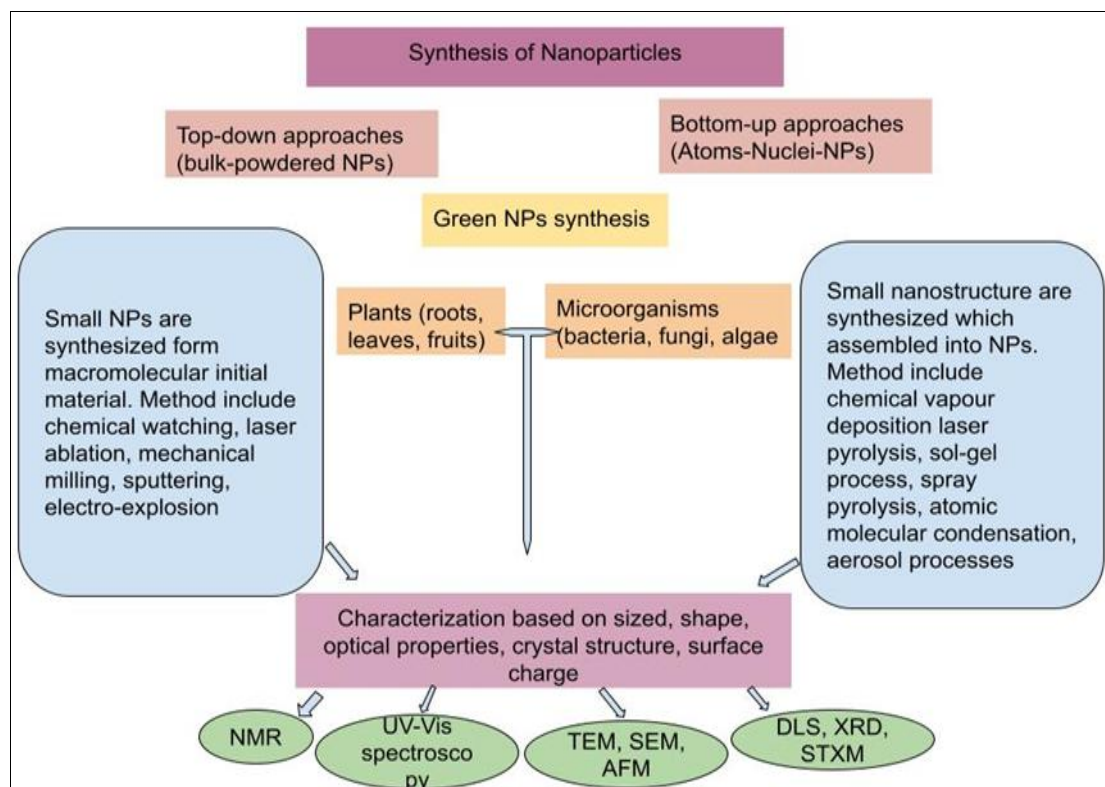


Fig 2: Synthesis and characterization of nanoparticles

7. Conclusion

This review paper discusses the use of nanotechnology to improve plant resilience against stress, as well as climatic change. It explains how nanotechnology can donate to supportable crop production through various features. The use of nanotechnology has shown to improve plant resistance to changed types of stress. The article highlights the important of nano fertilizers, nano pesticides and nano sensors in precision agriculture. The use of nanocarriers in biomolecule delivery is another application of nanotechnology that requires further research. The review also focuses on the mechanisms of using nanomaterials to improve crop resilience. However. More investigation is needed to gain a thorough grasp of the multitude of factors related to the application of nanotechnology to plant resilience.

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9. Conflict of interests

The authors declare that there is no conflict of interest.

10. Authors contributions

Conceptualization; Nitin Kumar ;Investigation; Shailja SharmaMethodology; Nitin Kumar ; Supervision;Amandeep Kaur;Roles/Writing - original draft;Shailja Sharma and Nitin kumar and Writing - review & editing; Nitin Kumar; Figures making; Shailja Sharma

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12. Data availability

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13. Ethics statements

This article does not contain any studies on human participants or animals performed by any of the authors.

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