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Revolutionizing Crop Production: Nanoscale Wonders-Current Applications, Advances, and Future Frontiers

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REVIEWING Agri-nanotechnology from the perspective of nanoparticles and crops will help us better understand the interactions between nanoparticles and crops, such as uptake, mobilization, and accumulation. In recent years, a great deal has been accomplished in nanotechnology in biomedical sciences, revolutionizing therapeutic and diagnostic techniques. Despite that, additional research is introducing the NPs on plant development and agroecosystems for smart nontechnological approaches for crop enhancement. Here, we have swiftly introduced NPs used in plant science and described the methods of application uptake, mobilization, and biological effects of NPs on crops. Intending to invigorate plant safety or promote plant progression and development that affected crop production. This review examines the essential present applications of NPs in agriculture while also exploring the potential application of NPs in a regulatory manner, which could open novel and harmless possibilities for the intelligent delivery of biomolecules and for novel tactics in crop nutrient management, crop genetic engineering, and battling against abiotic stresses in climate change era.

Keywords: Agri-nanotechnology, crops protection, production, abiotic stresses, crop genetic engineering, climate change.

1. Introduction

Ensuring food security for a continually growing world population is our planet's biggest global difficulty (Rajput et al., 2021). Food consumption is projected to increase from 59 to 98% by 2050 when the number of people worldwide will exceed 9 billion (Prasad et al., 2017a). Demand in food supply needs higher production of crops that require much more agricultural resources e.g., fertilizers, insecticides, pesticides, herbicides, and plant growth substances (Barrett, 2021). Higher uses of these agricultural resources may be helpful for higher production of agricultural goods but the accumulation of chemicals has affected human health (Leaver, 2011; Chen et al., 2014). Farmers worldwide concentrate on employing new ideas and technologies to increase crop yield through intensive and vast farming. Nanotechnology-enhanced stimulants and targeted farming practices are currently being used to bolster ongoing efforts (Singh Sekhon, 2014b). Advances in nanotechnology research could improve fundamental aspects of food security, including agricultural productivity, soil progress, use of safe water, food dispersal in stores, and food quality (Figure 1) (Ashraf et al., 2021). The Greek term nano means one billionth part of something. One billionth of a meter is equivalent to one nanometer. Nanotechnology is the field of study focused on the manufacturing and alteration of substances on the nanometer scale. To secure the long-term health of the nation's economy and population, as well as to fortify food security, it is vital to invest in advanced technology that will both amplify production and minimize food waste. By increasing the bioavailability of nutrients and

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providing a more convenient, more manageable form for food production, nanotechnology presents a promising new approach to high-quality food production. Enhancing the practice of nanotechnology in the food and agricultural industries is the subject of numerous studies.

Due to generous public support, nanotechnology in agriculture has made significant advancements in the last decade. This could be due to the unrestricted pattern of farm production, where energy and matter are consistently being exchanged. The absence of control over the input of the NPs makes the need for input materials always considerable compared to industrial nanoproducts (Mukhopadhyay, 2014; Faizan et al., 2023). Heightened crop yields are possible with the help of new agrochemical agents made available by nanotechnology and new delivery mechanisms that promise minimizing pesticide use (Singh Sekhon, 2014a; Sári et al., 2024). Nanotechnology applications in agriculture comprise nano-formulations of agrochemicals for administering pesticides and fertilizers for harvest improvement, enhanced harvest yields without affecting the state of the soil or water availability, and precision farming techniques (Haris et al., 2023). Nitrogen depletion from leaching, emissions, and soil microorganisms can also be decreased because of climate change or wrong agriculture practices. With the help of NPs, base fertilizers can enhance the nitrogen content and other soil nutrients (Guleria et al., 2023). Nanotechnology can transfer genes or DNA using nanoparticles to generate insect-resistant plant varieties (Ali et al., 2021). It can also enhance the effectiveness of food processing and storage and prolong the shelf life of many foods (Salama et al., 2021). Biomass-to-energy production could see more progress with the assistance of nanotechnology. Agricultural utilization of nanomaterials seeks to lower the need for pesticide spraying and enhance crop yields (Mishra et al., 2019). Diseases can be detected and managed with nanotechnology tools like nano-capsules and nanoparticle-based sensors (Nandini et al., 2023). Furthermore, the application of nanotechnology-derived devices in plant breeding and genetic transformation is being researched. (Singh et al., 2021).

Nanotechnology has enormous promise in the agricultural sector, however, several concerns must be resolved as part of the risk appraisal. (Zhang et al., 2022). Nanoparticle enticers constructed from biopolymers such as proteins and carbohydrates have little impact on human wellness and the natural world. Nanotechnology has numerous uses in the agricultural sector, including production, processing, storage, packaging, and transportation (Prasad et al., 2017b). Agriculture practices, plant nutrient uptake, disease recognition, and pest management are a few illustrations through which nanotechnology will revolutionize the farming and agriculture industry (Shang et al., 2019; Okeke et al., 2022; Abd El-Aty et al., 2024).

As part of this review, we examine all nontechnological aspects that contribute to sustainable agriculture crop production.

2. Fundamentals of NPs

The size, shape, organization, similarity, and grouping of NPs are the most common criteria for categorizing them. Circular, crystalline, and flat NPs are the three most current morphologies to be found. According to the dimension of electron movement, there are four categories of NP: Dimension 0; 1D thin films are employed in sensor mechanisms and electronic devices. Second-generation NPs are present in 2D-like nanotubes made of carbon, which have great absorption and stability; and 3D includes dendrimers and quantum dots (Pokropivny and Skorokhod, 2007). Depending on their chemical compositions, these are additionally categorized into carbon-containing, organic, and inorganic NPs. (Tiwari et al., 2012). Non-carbon-based materials are used to produce inorganic NPs, which can be further broken down into two types: metals and metal oxides. Materials like gold, silver, copper, iron, zinc, cadmium, cobalt, and platinum are utilized to synthesize NPs (Zn) (Jeyaraj et al., 2019). These NPs vary in terms of their shapes, sizes, densities, and surface areas. The primary goals of synthesizing metal oxide NPs are to boost their performance, regulate their reactivity, and adjust their properties (Jeyaraj et al., 2019). NPs are manufactured through oxides like Al_2O_3, CeO_2, Fe_2O_3, ZnO, SiO_2, and titanium oxide (TiO_2) (Wang and Xia, 2004). Green nanoparticles consist of green polymers like liposomes, ferritin, micelles, and dendrimers. Micelles and vesicles can be harmed by electromagnetic radiation and the heat effect (Dhand et al., 2015a). The non-toxicity and efficacy of these particles make them ideal for use in targeted drug delivery. Carbon particles are made from carbon and have many agricultural uses e.g., nanofibers, graphene, carbon black, carbon nanotubes, and fullerenes (Dhand et al., 2015b). There are two principal procedures used to make NPs: First, a top-down strategy, in which the synthesis commences with the large form and methodically removes pieces at a time to create tiny NPs (Sapsford et al., 2011).

The second method is a top-down approach, in which the synthesis begins with the NPs themselves. To mass-produce NPs, both top-down strategies, such as photolithography, electron beam lithography, milling approaches, anodization, ion and plasma etching, and bottom-up tactics such as the assembly or amalgamate of molecules and atoms, have been employed (Wang and Xia, 2004). Bottom-up synthesis includes the building of CVD (chemical vapor deposition), laser pyrolysis, polymer/monomer compounds, bio-assisted synthesis, flame or plasma spraying synthesis, and electrochemical or chemical nano-structural precipitation, (Wang and Xia, 2004). A rough classification of synthesis techniques for NPs can be made into three types: physical, chemical, and assisted (Wang and Xia, 2004).

3. NPs delivery methods, uptake and translocation process

3.1 Soil Application and uptake of NPs

In the soil, NPs go through a variety of bio/geo-transformations that impact their bioavailability and toxic effects. After interacting with roots systems, NPs migrate to aerial segments and gather in cellular or subcellular organelles. The uptake of NPs from the soil through plant roots is the initial step in bioaccumulation(Nair et al., 2010; Rajput et al., 2020). Furthermore, it has been observed that tiny NPs (diameters ranging from 3 to 5 nm) can permeate plant roots via capillary forces or directly pass through root epidermal cells (Lin and Xing, 2008; Xu et al., 2022). The primary epidermal cells construct a semipermeable cell wall with tiny pores that effectively restrict the large-size NPs. Initial pore formation in the epidermal cell wall simplified the uptake of some NPs (Du et al., 2011; Dong et al., 2022). When NPs penetrate cell membranes, they move via extracellular gaps till they hit the central vascular cylinder, allowing the xylem to ascend vertically. To get access to the central vascular cylinder, NPs must cross the Casparian strip boundary via a symplastic way (Figure 2B, and 2C). This happens through endocytosis, pore establishment, and delivery after attaching to carrier proteins in the membrane of endodermal cells. NPs, embedded in the cytoplasm, can move across cells via plasmodesmata (Pérez-de-Luque, 2017; Tripathi et al., 2017b). The Casparian barrier gathers the NPs that can't get inside the plant, while the shoots and roots accept the NPs that have reached the xylem (Wang et al., 2012). Absorbed NPs may be placed in the outer layer cell membrane, cortical cell inner environment, or centers of plants conversely, non-absorbed NPs on the root surface of a soil aggregate can change nutrient absorption (Wang et al., 2012; Tripathi et al., 2017b). When laying the seed on the soil, seeds can take in the soil-blended NPs instantly through the coat using parenchymatic intercellular spaces, with consequent NP diffusion in the cotyledon (Tripathi et al., 2017b; Avellan et al., 2021; Zhang et al., 2021).

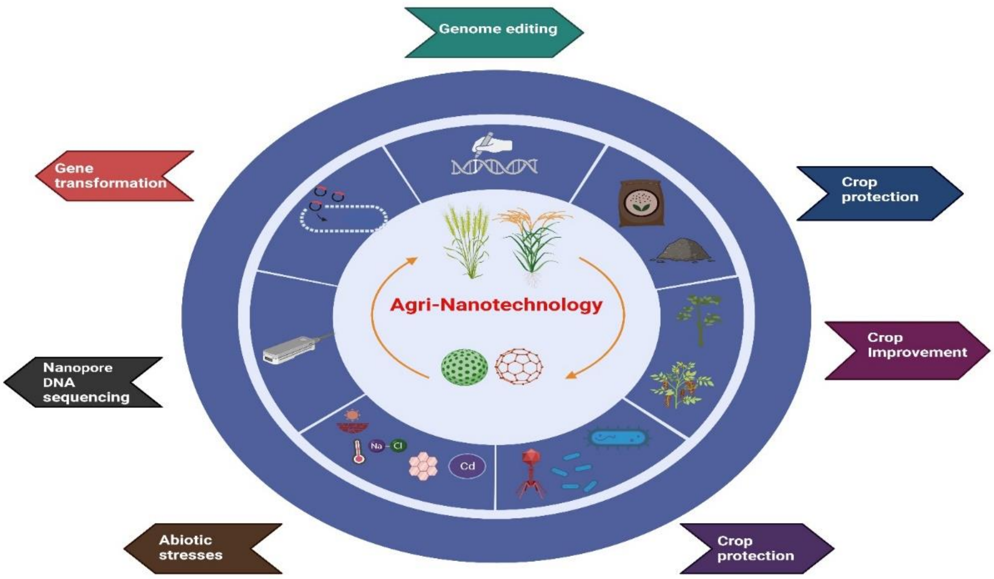

Fig. 1. Diagrammatic repreparation of application of agri-nanotechnology in various fields of agriculture.

In agriculture, foliar sprays of engineered nanoparticles (NPs) are used more and more as nano-fertilizers, nano-pesticides, nano-sensors, and nanocarriers. When matched to the standard process of soil-root treatment, the efficacy of plant protection technologies is enhanced when NPs are sprayed directly onto the leaves. Spraying foliar solutions with NPs allows them to go into the plant primarily through the stomata and then travel throughout the plant via apoplastic and symplastic pathways (Figure 2 A). The practice of foliar NPs has been revealed to increase crop yield and quality and plant defenses against pests and diseases. The processes by which foliar NPs trigger harm, however, remain to be fully elucidated. In addition, the chemical and physical features of NPs, as well as the abiotic factors like temperature, humidity, and light, should be explored to better this technology's ability to enhance the foliage uptake of NPs. The NPs that are put on the leaves can get in through the stomata or cuticles (Elmer et al., 2021). The cuticle is the first line of defense for a leaf, preventing particles smaller than 5 nm from entering the plant. They get into the plant through stomata, and their cells place them in the plant's vascular system through apoplastic and symplastic pathways (Zhao et al., 2012). NPs that are between 10 and 50 nm tend to move through the cytoplasm of the cell next to them (symplastic route). Thus, NPs ranging in size from 50 to 200 nm migrate between cells (apoplastic pathway).

Adopted NPs travel through the phloem sieve tubes with the sugar solution. Roots stems, fruits, grains, and young leaves all act as powerful sinks for the sap, so NPs can move in both directions as they are transported via the phloem in the plant's vascular system (Sivanesan et al., 2023). As a nonselective path of least resistance, the apoplastic pathway is well-known. It is commonly accepted that the apoplastic route is the most efficient for translocating numerous water nutrients and non-essential metal complexes (Ma et al., 2023). Applicable adsorption of NPs following foliar application was determined by application method, NP size and concentration, and environmental conditions (Wang et al., 2013). Many factors, including the morphology of leaves and chemical composition, trichrome presence, and the presence of leaf exudates and waxes, influence the ambushing of NPs on the leaf surface (Dong et al., 2022).

3.3 Translocation of NPs

The plant's body translocation is divided into two important parts apoplast and symplast. In apoplast-based translocation of nutrients via interconnected cellular membranes found on the inside of plant cells. On the other hand, symplast-based translocation of nutrients occurs via protoplasts of different plant cells that are connected by a thin cytoplasmic connection. These are two routes through which dissolved ions can take into and out of the roots. Ions can only enter roots cells through symplastic pathways via membrane-specific channels and transporters that allow them to cross the plasma membrane (Figure 3). It has been shown that apoplastic transport encourages the radial motion of NPs, which could deliver NPs to the root's core cylinder and vascular tissues, thereby facilitating their ascent into the aerial part of the plant. This method of NP translocation is particularly useful for those uses that call for systemic NP delivery. However, a layer of lignin-like structures called the Casparian strip prevents the root endodermis from completing its radial migration. NPs must eventually enter cells to undergo symplastic transport. Plant cells are more challenging than animal cells to deliver NPs intracellularly since they have a strong cell wall that functions as an external barrier to cell entrance. Cells have been characterized with alternative cell entry strategies such as those based on hole creation, membrane translocation, or carrier proteins (Nel et al., 2009). Plasmodesmata which are cytoplasmic bridges (membrane-bound) having an adjustable diameter (20-50nm), aid in the migration of NPs from one cell to another after they penetrate the cytoplasm. Arabidopsis, rice, and poplar have all been studied to describe the transport of NPs of varying sizes through plasmodesmata (Pérez-de-Luque, 2017).

Small particles can translocate throughout the entire plant via the symplastic and apoplastic passageways, making their way to the xylem and phloem vessels. Interestingly, NPs tend to accumulate in organs that have a high capacity to bring in fluids from the phloem (sink activity), such as flowers, fruits, and seeds. Concerns about NP buildup in particular organs are equally as chief as concerns about NP toxicity in plants (Pérez-de-Luque, 2017).

4. Recent Applications of Agri-Nanotechnology

4.1 Crop production

Crop productivity can be increased significantly through the application of nanotechnology in crop management. Nanoparticles enable the controlled spread of chemicals, the reduction of nutrient shortfall during fertilization, and an expansion in crop quality and yield (Figure 3) (Sangeetha et al., 2021). Chemical fertilizers are widely used because they are more proficient and profitable than other types of fertilizers (Pokropivny and Skorokhod, 2007; Chen et al., 2020b). However, excessive or improper use of chemical fertilizers can damage soil, reduce crop yields, and pollute the surrounding environment. For example, urea, which is very water-soluble and easy to lose, meets 80% of plants' needs for N-fertilizers (Chen et al., 2020b). The application of any N compound to a paddy field results in leaching due to liquidation, denitrification, volatilization, and runoff. N is lost principally as nitrate through leaching and denitrification, about 10-30% through volatilization, and about 2-30% through ammonia (Pokropivny and Skorokhod, 2007). The liberation of excess nitrogen into the environment leads to eutrophication in water and air. Toxic algal blooms and the deaths of marine life are just two of the many negative consequences of eutrophication, which also threaten freshwater supplies.

Nano-fertilizers are essential for enhancing crop yield. Utilizing nano fertilizer can help stop eutrophication and water pollution. This substance improves the supply of nutrients to plants and manages the steady and precisely controlled release of nutrients into the soil (Pokropivny and Skorokhod, 2007). The potential use of nano-fertilizers has emerged as a promising strategy for addressing environmental concerns linked to traditional fertilizers and their role in eutrophication and water pollution. Eutrophication, marked by the influx of excess nutrients—often from agricultural runoff—triggers imbalances in water ecosystems, fostering undue plant and algae growth, oxygen depletion, and detrimental impacts on aquatic life (Ha et al., 2019). Nano-fertilizers, distinguished by their diminutive particle size, offer a solution by improving plant nutrient uptake efficiency and mitigating nutrient runoff. Through controlled and gradual nutrient release, nano-fertilizers can enhance plant absorption, reducing the likelihood of excess nutrients reaching water bodies (Das et al., 2016). Their potential benefits include improved nutrient efficiency, diminished environmental impact compared to conventional fertilizers, heightened plant uptake efficiency owing to smaller particle sizes, and customizable formulations for specific crops and soil types. Despite these advantages, it is imperative to acknowledge that the long-term environmental and health impacts of nano-fertilizers remain under scrutiny. Concerns encompass the potential accumulation of nanoparticles in soil and water and unintended effects on non-target organisms. Additionally, the scalability and cost-effectiveness of nano-fertilizer production pose challenges to widespread adoption.Nano fertilizers made from banana peels were used to grow tomatoes, peppers, or flowers (Sivarethinamohan and Sujatha, 2021). Nano fertilizers were exercised to grow and improve different crops e.g., nanoparticles of ZnO were used to grow chickpeas, silicon, and iron slag powder were used to grow maize, colloidal silica, and NPK was used to grow tomatoes, TiO_2 was used to grow spinach and gold, and sulfur was used to grow grapes (Sivarethinamohan and Sujatha, 2021).

In soil incubation experiments, $CaSO_4$ reduced the wastage of phosphorus from agricultural land and $CaSO_4$ is a typical soil conditioner that has a robust complexation to orthophosphate (Sivarethinamohan and Sujatha, 2021). Nano calcium sulfate may minimize soil phosphorus loss even more than typical crude $CaSO_4$ because of its larger area of surface, greater solubility, and superior fertilizer-soil integration. To decrease chemical depletion and related ecological problems, it is possible to utilize nanoscale carriers in fertilizer application in such a manner that they fix the plant’s roots with the encompassing soil contents and organic material (Lin et al., 2009). Soil toxicity can be lowered by using nanoscale fertilizers, mitigating some of the unintended consequences of using a high dose (Davari et al., 2017). The nutrient release from these nano fertilizers is slowed, and the fertilizer’s effects last longer (Naderi and Danesh-Shahraki, 2013). Significant consequences of TiO_2 nanoparticles on maize growth have been observed, and the combination of SiO_2 and TiO_2 nanoparticles has been shown to increase plant absorption potential and enhance nitrate action, leading to more effective water and fertilizer management (Naderi and Danesh-Shahraki, 2013; Singh Sekhon, 2014c).

4.1.1 NPs based macronutrient nano-fertilizers

One or more of the macronutrient elements (N, P, K, Ca, and S) make up macronutrient nano-fertilizers, which supply plants with high concentrations of these elements. Global demand for macronutrients is expected to climb to 263 Mt by 2050. (Alexandratos and Bruinsma - FAO, 2012). It has increased food production per person by around 40% over the previous 50 years, primarily due to the widespread use of nitrogen fertilizer (Smil, 2002). Nonetheless, massive amounts of N, P, and K fertilizers are eventually carried into surface and groundwater, causing catastrophic damage to aquatic ecosystems (Liu and Lal, 2015). Thus, it is essential to create highly effective and environmentally benign macronutrient nano-fermenters in order to attain sustainable food production while also preserving the natural world. The three most crucial nutrients for plant development and growth are N, P, and K. Soil requires N in liquid as well as solid forms, such as ammonium, urea, nitrate, and anhydrous ammonia (Liu and Lal, 2015). Apatite NPs, monopotassium phosphate, and N-doped carbon dots are only a few examples of the many types of NPK nano-fertilizers.

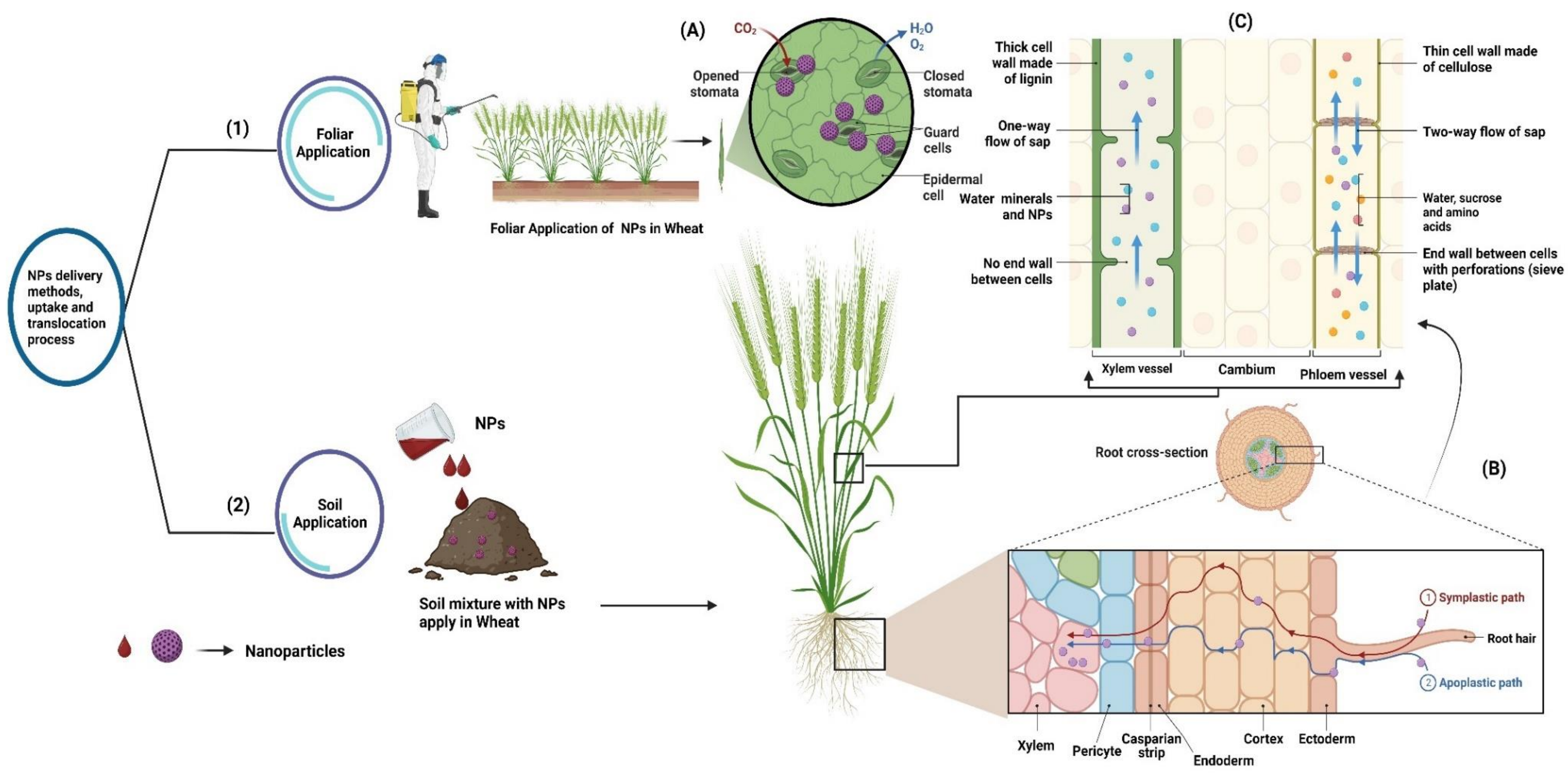

Fig. 2. Application methodology of NPs through foliar (figure 1) and soil application (figure 2). The NPs which apply through (A) foliar method uptake by plants through stomata and soil mixture NPs transport via (B) symplastic and apoplastic pathways through (C) xylem and phloem in different parts of plants.

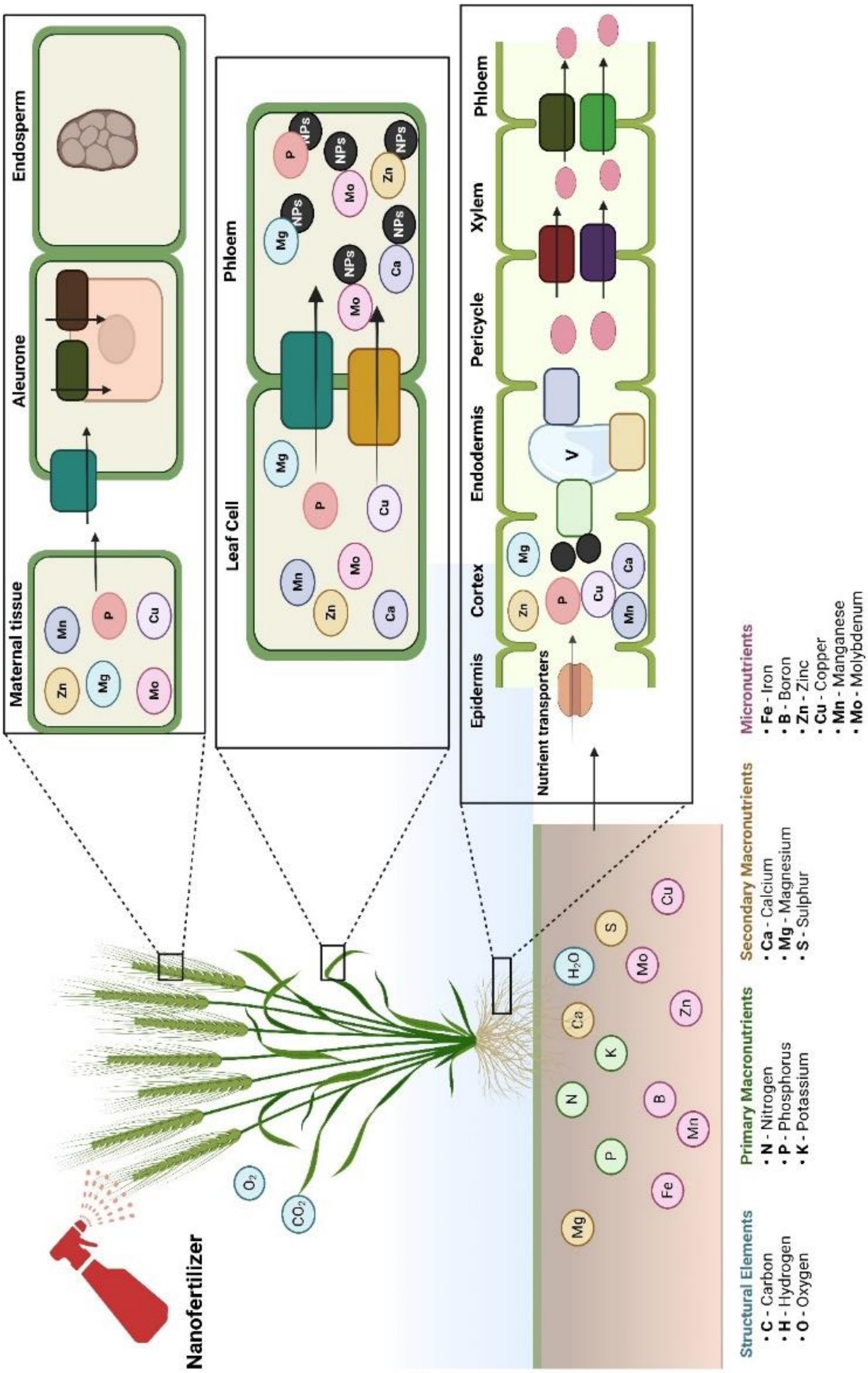

Fig. 3. Diagrammatic repreparation of nanofertilizers as source of plant nutrients that help crop production. This nanofertilizers helps in plants growth and developments and improve nutrients contents in grains.

Fertilization methods and growth enhancers have been compiled in **Tables 1, 2 and 3** (Liu and Lal, 2014; Wang et al., 2019; Sassine et al., 2020). These nano-fertilizers are very small diameter (20 nm) and soluble in water. They have considerably increased plant growth when added to fertilizer solution or water and then applied to foliar sprays or poured directly onto the soil (Liu and Lal, 2014). As a bonus, composite nano-fertilizers that supply multiple nutrients (such as monopotassium-phosphate) demote the negative influences of abiotic stress (like salt stress) on plant growth. The aforementioned three macronutrients, calcium, and sulfur are also crucial (Liu and Lal, 2014). Both calcium oxide NPs and sulfur NPs have been used to treat foliar and soil when diluted in water (Salem et al., 2016). These nano-fertilizers are utilized in more significant quantities than N, P, and K nano-fertilizers (Table 1), despite their wide and irregular sizes (20-80 nm). However, it should be mentioned that additional research is still desirable to guarantee their safety for widespread and longstanding agricultural applications, even though these various nano-fertilizers only comprise several harmless elements (i.e., C, O, N, K, P, Ca, and S) (Salem et al., 2016).

4.1.2 NPs based Micronutrient Nano-fertilizers

Micronutrients are necessary plant nutrients that are supplied in much smaller quantities (less than 10 mg/kg of soil) than macronutrients (Adisa et al., 2019). It is required for the synthesis of enzymes and biomolecules involved in plant defense. Furthermore, eating meals poor in micronutrients has negative impressions on human health, involving anemia, slowed growth, and impaired cognition (Adisa et al., 2019). Micronutrient nano-fertilizers such as zinc, copper, iron, manganese, and molybdenum must be applied to plants in addition to macronutrient nano-fertilizers (Adisa et al., 2019). Zn is a micronutrient that all living things, including humans, need. Zinc oxide nanoparticles (NPs) were used as nano-fertilizers in two separate investigations (Rossi et al., 2019). Both have particle sizes of roughly 50 and 70 nm. These ZnO-NPs take some time to dissolve in water. Yet, these ZnO-NPs and their collections are smaller in diameter than stomatal pores, demonstrating their ability to enter and migrate throughout plant tissues. Zn^{2+} may be continually released from NPs that have been affixed to leaf surfaces, giving plants a steady supply of Zn that they can take up through their stomata. ZnO-NPs enhanced the development and harvest of numerous plant species. The proper physiological role of plants and their nutritional property can be negatively impacted by the absence of Fe, a key nutrient comprised in chlorophyll production and the electron transport system (Rossi et al., 2019). Maghemite (-Fe_2O_3) NPs were used as nano-fertilizers that also improve resistance against drought stress in plants (Palmqvist et al., 2017). In addition, the levels of H_2O_2 were decreased, and the leaf development rate and chlorophyll content were both improved. Nevertheless, Fe_2O_3 NPs dissolve slowly and aggregate into larger particles with a hydrodynamic size of up to 500 nm. This additionally promotes the steady uptake of iron ions (Fe^{3+}) by plants over extended periods. Nanoscale zero-valent iron (nZVI) was used to improve soil quality and increase rice yields at the same time in a separate investigation (Palmqvist et al., 2017). Larger nZVI (100 nm) and lower coercivity (35.17 Oe) were shown to significantly increase both grain yield and the rate of pollution removed from the soil. When tested in soil, the other nZVI, which is minor and has an advanced coercivity, showed increased homo-aggregation, which has a detrimental effect on performance. For optimal plant and microbial development, Cu is another crucial micronutrient. Root and foliar applications of Cu-based NPs are important for plants (Table 1). These NPs include CuO, CuS, and $Cu(OH)_2$ (Liu et al., 2020). The dispersibility of the spindle-shaped $Cu(OH)_2$ NPs is greater than that of the spherical CuO and CuS NPs, which allows for greater uptake of Cu by plants (Spielman-Sun et al., 2018). The decreased dispersibility of CuO and CuS NPs means that they remain on the roots longer and continue to transfer Cu to the leaves of the plant after application (Spielman-Sun et al., 2018). Mn is an essential micronutrient for plant growth and development and necessary for the biochemical reaction of photosynthesis. Stable square-shaped Mn-NPs, with a hydrodynamic radius of around 100 nm, can be distributed in water without aggregation, and their particle size after dispersion remains within the nanoscale range. The reduced size of these Mn-NPs-based nano-fertilizers allows plants to more easily absorb them, and they are safe even at larger concentrations (Pradhan et al., 2013).

Table 1. Application Agri-Nanotechnology in various fields of agriculture (nanofertilizers for crop production).

Applied NPs	Applied Method	Applied concentration	Mode of action	References
ZnO-NPs	Foliar	5 g L^{-1}	Rice (*Oryza sativa* L.) growth, yield, characters that affect yield, microbial counts, and the activity of the dehydrogenase enzyme all began to improve	(Bala et al., 2019)
	Foliar	10 mg L^{-1}	Coffee (*Coffea arabica* L.) plant was an increase in net photosynthetic rate (55%), fresh weight (37% roots, 95% leaves), and dry weight (28% roots, 85% leaves).	(Rossi et al., 2019)
	Foliar	10 mg L^{-1}	Clusterbean (*Cyamopsis tetragonoloba* L.) enhancements to growth physiology and a rise in biomass accumulation and nutrient concentration	(Raliya and Tarafdar, 2013)
	Soil irrigation	0–1000 mg L^{-1}	Peanut (*Arachis hypogaea* L.) increased rates of photosynthesis, plant growth, morphological diversity, crop yields, and overall plant efficiency	(Prasad et al., 2012)
$nCeO_2$	Soil	0–500 mg kg^{-1} soil	Barley (*Hordeum vulgare* L.) increased plant functioning, increased Ce deposit in grains, and increased P, K, Ca, Mg, S, Cu, Fe, Zn, Mn, Al, amino acids, fatty acids, methionine, aspartic acid, threonine, arginine, and linolenic acid.	(Rico et al., 2015)
N-CDs	Nutrient solution	0.2 mg L^{-1} Nitrogen-doped carbon-dots	Mung bean (Vigna radiata L.) increased its growth rate by 200 percent (average length of shoots and roots).	(Wang et al., 2019)
MKP	Foliar and soil	3 g L^{-1} Mono-potassium-phosphate	Tomato (*Solanum lycopersicum* L.) growth parameters were enhanced despite the presence of salt stress	(Sassine et al., 2020)

Table 2. Application Agri-Nanotechnology in various fields of agriculture (nanopesticides for crop protection).

Applied NPs	Nano-pesticide Type	Target Pests/ Insects/ Herbicide/ plant	Mode of action	References
Silver	Nano viricides	*Solanum tuberosum*	Tomato *(Solanum lycopersicum L.)* reducing TSWV infections and preventing localised damage	(Shojaei et al., 2016)
Zinc oxide	Nano viricides	Tobacco mosaic virus (TMV)	Acceleration of TMV invasion suppression in *Nicotiana benthamiana*	(Cai et al., 2019)
Iron oxide	Nano viricides	Tobacco mosaic virus (TMV)	Activated antioxidants defense system in *Nicotiana benthamiana* and induction of resistance to TMV by upregulating SA genes	(Cai et al., 2019)
Chitosan/ tripoly-phosphate	Nano herbicides	Paraquat	Eco-friendly weed control in maize and mustard using paraquat-doped chitosan/tripolyphosphate nanoparticles	(Grillo et al., 2014)
Chitosan	Nano herbicides	*E. crus-galli*	Nanoparticles of maize carboxymethyl chitosan for the controlled liberation of glutathione-sensitive herbicides	(Yu et al., 2015)
PVC (Polyvinylchloride)	Nano insecticides	*P. vulgaris, Phaseolus vulgaris; P. xylostella, Plutella xylostella; S. hortensis, Satureja hortensis L.; S. litura, Spodoptera litura*	Birch and southern yellow pine NPs-based biocides that are sprayed on the leaves have different effects on plant growth	(Liu et al., 2002)
Silica	Nano insecticides	Cotton bollworm (*H. armigera*)	Compared to conventional insecticides, silica nanoparticles loaded with *Brassica chinese* chlorfenapyr are more effective and have a lower toxicity profile	(Song et al., 2012)
Polyvinylpyridine (PVP) and PVP-co-styrene	Nano fungicides	*G. trabeum*	Sapwood of a southern pine Tebuconazole and chlorothalonil, two fungicides, were slotted in into polymeric nanoparticles. Specimens of Southern pine sapwood have been bottled with biocide-containing nanoparticles and then uncovered to the wood decay fungus *Gloeophyllum trabeum* in a straightforward water trial.	(Liu et al., 2002)
Chitosan/ Pectin	Nano fungicides	*F. oxysporum and A. parasiticus*	Corn, and Cucumbers Seeds of *Cucumis sativa, Zea mays*, and *Lycopersicum esculantum* benefit from a fungicide formulated for tomatoes called carbendazim nano	(Kumar et al., 2017)
Chitosan	Nano fungicides	*F. graminearum*	The maize pathogen Fusarium graminearum can be stunted by using chitosan nanoparticles encapsulated with the essential oil of the *cymbopogon martinii* plant.	(Kalagatur et al., 2018)

Table 3. Application Agri-Nanotechnology in various fields of agriculture (nanopesticides for gene transformation).

Applied NPs	Applied method	Targeted plant and dose	Mode of action	References
SWCNTs/ MWCNTs	Gene transform/ Co-culture	*N. tabacum*	With *N. tabacum* leaf explants, the rate of callus formation and regrowth of shoots from the callus touched 100% by the third week of cultivation on the medium	(Burlaka et al., 2015)
SWCNTs	Gene transform/ Needleless injection	Leaves of tobacco	Silencing endogenous genes (GFP) in intact plant cells was achieved using SWCNTs, which also served to shield the siRNA from nuclease degradation	(Demirer et al., 2020)
MSNs	Gene transform/ Spray and needleless injection	Leaves and roots of tomatoes	The exogenous genes were introduced into plants using the MSNs-based transient expression system, which then carried out transcription and translation in the appropriate plant tissues	(Hajiahmadi et al., 2019)
DNs	Gene transform/ Needleless injection	Leaves of *N. benthamiana*	When compared to the control groups, the GFP fluorescence intensity dropped the most in the leaves that were injected with siRNA-DNs	(Zhang et al., 2019)
CDs	Gene transform/ Leaf spray	Leaves of *N. benthamiana* and tomato	GFP transcript and protein levels were found to be reduced by over 80%.	(Schwartz et al., 2020)
CaP-NPs	Gene transform/ Co-culture	*Brassica juncea* L. cv. *Pusa Jaikisan*	When compared to Agrobacterium tumefaciens (54%) and naked DNA (8%), the transformation efficacy was roughly 80% when using a CaP-based delivery platform	(Naqvi et al., 2012)
Gold nano-particle	Genome editing CRISPR/Cas 9 /	Wheat	Hexaploid wheat gene targeting with CRISPR/Cas9 and DNA replicons	(Gil-Humanes et al., 2017)
Fe_2O_3-NPs	Salinity	0, 10, 20 and 30 µM	Fresh and dry weight, phosphorus, potassium, iron, zinc, and calcium content, and antioxidant enzyme activity all rise in peppermint (*Mentha piperita* L) leaves	(Askary et al., 2017)
Cu-NPs	Salinity	50, 100, and 150 mg/L	Improved tomato (*Solanum lycopersicum* L.) yield, immunity, and mineral content	(Hernández-Hernández et al., 2018)
Mn-NPs	Salinity	0.1, 0.5, and 1 mg/L	The mineral content of capsicum (Capsicum annum L.) plants differed between their shoots and roots.	(Ye et al., 2020)
Cu-NP	Drought	3.33, 4.44 and 5.55 mg/L	In response to drought, maize (*Zea mays* L.) increased both total seed number and grain production.	(Nguyen et al., 2020)
ZnO-NPs	Cu and Pb heavy metal stress	5, 10, 15, 20 and 25 mg/L	Lowered metal uptake in rice (*Oryza sativa* L.) and increased photosystem and thylakoid membrane strength	(Akhtar et al., 2021)
Se-NP	Heat stress	10 mg/L	Improved chloroplast strength of Sorghum *(Sorghum bicolor L.)*	(Djanaguiraman et al., 2018b)

4.2 Crop protection

The conventional method of pest control involves the unsafe application of fungicides, herbicides, and insecticides, with about 90% of the formulations being lost to the environment rather than reaching the target site (Mishra et al., 2019). Every year, plant pests and microorganisms cause a worldwide average annual crop decline of 20-40% [52]. Insecticides, fungicides, and herbicides, all forms of pesticides, are essential for contemporary farming's pest control strategies. Effective and less polluting pesticides must be developed. Nanotechnology and other new ideas can make agrochemicals safer, last longer, and dissolve better in water and all these nano-agrochemicals could be advantageous for the environment (Chand Mali et al., 2020). The primary component in nano-pesticides is released gradually following the requirements of plants (Ul Haq and Ijaz, 2019). The utilization of NPs decreases the unhelpful effects of standard pesticides on humans, pollinators, and the environment (Figure 3), and strengthens the efficiency of standard pesticides in total (Ul Haq and Ijaz, 2019). These chemicals do more harm to the environment than good, including the ineffective suppression of pests, pathogens, and weeds. For plants to be protected from insect pests, the active ingredient must be present in a threshold concentration, and one such method is nanotechnology, where the key component of the chemical formulation has been enclosed within nanomaterials (de la Rosa et al., 2021). In contrast to traditional pesticides, which are highly soluble and can damage plants around the pointed species, resulting in the target species developing a resistance to the pesticide, encapsulated pesticides last for long periods, releasing the necessary quantity of active constituent at the target site (de la Rosa et al., 2021). It has been found that inorganic nanoparticles (ZnO, Cu, SiO_2, TiO_2, CaO, MgO, MnO, and Ag) are effective against microbes in plants (Tang and Zheng, 2018). Nano pesticides are effective against numerous field and stored grain pests (Zhao et al., 2018). Chitosan alginate (nano-formulation) in conjunction with paraquat reduced the toxicity of paraquat alone. Several types of phytopathogenic bacteria, yeasts, and fungi were killed by copper nanoparticles. The aquatic weed *Eichhornia crassipes* was successfully managed through the use of silver nanoparticles-chitosan encapsulated paraquat (Zhao et al., 2018). In general, nanoparticles can be used to protect plants in two ways: (a) the nanoparticles themselves can protect crops, or (b) nanoparticles can be employed as pesticide carriers and sprayed on plants (Sharma et al., 2017; Worrall et al., 2018). NPs have many potential applications, but they have only recently begun to be investigated for utilization of Cn in agricultural settings.

4.2.1 Nano-insecticides

At least 90% of applied pesticides either fail to control insects effectively or are dispersed throughout ecosystems (Paramo et al., 2020). The environmental costs and agricultural inflation caused by this scenario are both unacceptable. The formulation's active ingredients must be present at the target site in the lowest effective concentration to provide adequate protection against insect invasion and crop loss (Table 1). The use of nanotechnology in the encapsulation and formulation of insecticides has revolutionized the industry of crop protection (Figure 4). The active ingredients of insecticides can be encapsulated in NMs of varying sizes through a technology called nano-encapsulation (Paramo et al., 2020). Some of the particles used in the nano-formulation of insecticides can serve as active substances and other designed nanostructures have insecticidal properties (Kah and Hofmann, 2014). Insecticides that have been nano-encapsulated or nano-formulated are more effective because the active ingredients are released gradually and remain in the plant or root zone for longer. Conventional formulations of insecticides not only cause resistance in the targeted insects but also harm non-target organisms by reducing the insecticide's water solubility. The aforementioned restrictions can be beaten with the aid of nano-encapsulation and nano-formulation (Kah and Hofmann, 2014). Insecticides that have been nano-encapsulated or -formulated have many desirable properties, including those of higher solubility, crystallinity, biodegradability, stiffness, permeability, and thermal stability (Kah and Hofmann, 2014). For instance, a pheromone formulated in nanofibers does not affect mortality in oriental fruit moths (*Grapholita molesta* L.), indicating a sustained attract-and-kill effect from the insecticide and pheromone and a method of regulating their release (Rai and Ingle, 2012). In addition, research has shown that insecticide nano-formulations can aid in the development of plant-mediated universal resistance. To better control sucking or chewing insects, for instance, SiO2 nanosphere formulations can improve insecticides' penetration into plant tissues and access to cell sap (Rai and Ingle, 2012). NMs in insecticides, then, hold fantastic promise for controlling pests.

4.2.2 Nano-herbicides

Plants reproducing aggressively or spreading outside their usual habitat are known as weeds (Grillo et al., 2014). Herbicides are the constituent chemicals derived from biological and synthetic sources that stunt plant growth or eliminate them (Zhang et al., 2019b). Today's herbicides, which are often synthetic versions of endogenous hormones in different plants, can stunt the growth of desirable crops. While herbicides are effective at eliminating weeds, excessive use can have negative effects on plant growth and even human health (Manjunatha et al., 2016). Synthetic or biological herbicides can be transported effectively with the help of nanotechnology through the use of nanosized preparations or pesticide formulations based on NMs (Shang et al., 2019). Herbicides are used in various NPs to increase bioavailability and efficacy in weed control. The unique properties of NMs can be used to create a wide variety of herbicides. These properties include permeability, stiffness, biodegradability, crystallinity, thermal stability, and solubility. Because of their larger specific surface area, nano-herbicides improve the affinity for the target. Spraying efficiency is improved with the help of nano-encapsulated herbicides due to a decrease in splash losses and spray drift. Soil containing nano-herbicides can be used to kill weeds and weed seeds before they even germinate. Encapsulating herbicides like triazine and atrazine could lead to more efficient crop protection (Balah and Pudake, 2019). Most commercially available herbicides only target the plant's above-ground portions, leaving the tubers and rhizomes below intact and able to produce new weeds (Balah and Pudake, 2019). To kill off specific weeds, scientists have developed herbicide molecules that are encased in NPs to penetrate the roots and reach the regions in the roots that inhibit the glycolysis process (Manjunatha et al., 2016). As prolonged use of herbicides can result in their residue in soils preventing the growth of subsequent crops, detoxification of herbicide residues is essential for sustainable development (Duhan et al., 2017). Carboxymethyl cellulose nanoparticles (NPs) can remove up to 88% of atrazine herbicides from water (Duhan et al., 2017). As a result, nanotechnology can increase the effective range of herbicides and keep them active for longer.

4.2.3 Nano-bactericides

Bactericides are any chemicals, whether they are made in a lab or found in nature, that can stop bacteria from growing or kill them (Elmer et al., 2018). Misuse of bactericides has resulted in the rise of bacteria resistant to multiple drugs; this poses a serious threat on a global scale and is one of the most difficult obstacles to overcome in farming (Figure 5). Innovations made possible by nanotechnology offer promise for a solution to this issue (Elmer et al., 2018). Interactions between NPs and microorganisms are crucial to their efficacy.

In-depth familiarity with both the microbial biology and the physicochemical features of NPs is necessary for their successful development as NMs. *Ralstonia solanacearum, Fusarium oxysporum, Verticillium dahliae, Fusarium solani, Monilinia fructicola, Colletotrichum gloeosporioides, Botrytis cinerea,* and *Alternaria alternate* are some microbes that responsible for soil-borne diseases and metallic oxide NPs have been demonstrated an effective role to control the growth of these soil-borne diseases causing microbes (Elmer et al., 2018). In addition, soil microbial communities directly affect soil quality through processes like symbiotic relationships with decomposing nutrient cycling, terrestrial crops, and organic matter (DS et al., 2019). Therefore, the primary responsibility of agricultural systems is to preserve the rich biodiversity and biomass of soil microbes. Metallic oxide NPs like CuO and Fe_3O_4 NPs, significantly affect the diversity and abundance of soil microorganisms (Varympopi et al., 2020). Nanoparticles (NPs) offer promise for future development of effective antimicrobial agents due to their physicochemical properties.

4.3 NPs for plant genetic engineering

4.3.1 NPs-based plant transformation

Improved crop yields are the outcome of climate change, an expanding human population, and the use of biotechnology to confer anticipated genetic traits on plants. The cell walls of plants prohibit chemicals from entering the cells. To address the issue of DNA transmission in plant cells and transform plant genetics, numerous methodologies based on Agrobacterium transformation or biolistic approaches are applied throughout. These strategies have drawbacks due to their constrained host range and the significant plant damage they cause, which frequently halts plant growth. Although there has been progress in plant genetic engineering, it has lagged and has only recently seen significant advances. It has been proposed that nanotechnology-based approaches could potentially be employed to introduce genes or other compounds into plants with great efficiency and minimal toxicity because they are inexpensive, simple, and durable (Patil and Chandrasekaran, 2020).

Nanotechnology has had a profound effect on many areas of study, most notably the medical, energy, and industrial sectors. Chemicals and biomolecules have been introduced into plant and mammalian cell systems using nanotechnology-based technologies (Jia and Wang, 2014). However, NP-mediated plant biomolecule transportation has been discovered to be more challenging because of the presence of the built-in barrier supplied by the cell wall (SY et al., 2019). Gene transfer polymer-based NPs, metallic NPs, silicon-based NPs, and carbon-based NPs are the four types of nanoparticles. It has been proposed that as NPs protect the genetic cargo from cellular enzymatic destruction, like nucleases, they enable effective plant transformation (Finiuk et al., 2017). The genetic payloads delivered by the various NP types vary. In contrast to metallic NPs, which can only transport DNA as genetic cargo, carbon nanotubes (CNTs) can transport both RNA and DNA (Bates and Kostarelos, 2013; Karimi et al., 2015). Cells can receive RNA, DNA, and proteins that have been enclosed by polymeric NPs like PEG and polyethyleneimine (Silva et al., 2010; Hasanzadeh Kafshgari et al., 2015). DNA and proteins can be carried by silicon-based NPs. Some NPs, like carbon nanotubes (CNTs) and mesoporous silica (MNPs), can deliver genetic cargo into cells without any chemical or physical pretreatment, while others, like gold NPs and magnetic NPs (MNPs), do. Tobacco, cowpea, and arugula have all been reported to have NP-mediated passive delivery (Finiuk et al., 2017).

Editing systems may find NPs and other novel materials to be useful transport mechanisms. For this reason, a plant bombardment technique, with the wheat shoot apical meristems as the intended tissue (Demirer et al., 2019). In this research, the green fluorescent protein gene construct-coated gold particles were delivered to the L2 cell layer of wheat shoot apical meristems. This technology successfully changed wheat without the use of embryogenic callus culture, and it has the potential to be extended to other crops that have not effectively transformed using more traditional methods (Ahmar et al., 2021).

4.3.2 NPs-based plant genome editing

Gene editing is frequently utilized in agriculture and has the potential to alter plant breeding (Wang et al., 2016). The CRISPR/Cas system, an RNA-based guard system in prokaryotes that includes Cas endonuclease and CRISPR repeat spacer arrays, has been adequately used to modify the genome of plants (Miller et al., 2017). Plants have benefited from CRISPR/Cas genome editing through customary transformation and revival processes (Tan et al., 2020). The four key problems with crop genome editing are lesser efficiency of HDR, tissue culture, regeneration, and delivery. The CRISPR/Cas9 technique can be made more precise and effective with the help of NMs, which have the qualities of high throughput, differently charged, high tensile strength, and minute size (Demirer et al.). The precise delivery of CRISPR/Cas9 single guide RNA by NPs has ushered in an entirely novel phase of genetic engineering. MSNs (mesoporous silica nanoparticles) have also been employed to load recombined loxP sites into chromosomal DNA and transport Cre recombinase in immature maize embryos.

After the modified MSNs were delivered to the crop cells, the loxP fragment was acceptable integrated (Martin-Ortigosa et al., 2014). Cationic arginine gold nanoparticles Cas9En (E-tag)-ribonucleoproteins (RNP) transport of sgRNA in cultured cell lines shown substantial effectiveness (about 30%) of active nuclear or cytoplasmic gene editing, which can establish a significant milestone for crop science research (Finiuk et al., 2017). Although CRISPR/Cas9 technology has been greatly accepted in many crops due to current nanotechnology, other difficulties to crop genome editing should be conquered using agrinanotechnology-based techniques (Finiuk et al., 2017).

4.3.2 NPs-based plant gene sequencing

Gene sequencing made possible by nanotechnology has aided in the enhanced detection and application of plant trait means, thereby altering the plants' responsiveness to environmental pressures and diseases. Nanoparticles and quantum dots are highly accurate biological markers (Sharon et al., 2010). Nanotechnology and nanoscopy have made optical mapping of DNA possible (Levy-Sakin and Ebenstein, 2013). Genomic optical mapping provides direct access to detailed information about a cell's genetic and epigenetic makeup. Nanopore sequencing has the potential to remove the constraints of short-read data by allowing the sequencing of individual DNA molecules with lengths of tens of kilobase pairs (perhaps up to 100 kbp) (Levy-Sakin and Ebenstein, 2013). Genomics applications of nanotechnology include molecular diagnostics, genome sequencing, noncoding RNA expression profiling, identification of binding sites of transcription factors, and targeted sequencing (Elingarami et al., 2013).

4.4 NPs for abiotic stresses

4.4.1 Salinity stress

The increased salt content of the soil is a direct result of the irrigation of agricultural regions around the world with salty water, which is itself a direct result of the water scarcity caused by global warming. One of the major problems with modern farming is salinity, or the deposition of too much salt in the soil, which prevents plants from growing normally and nearly destroys them (Isayenkov and Maathuis, 2019). When the concentration of NaCl reaches above 200 mM, most plants perish. Seed germination, seedling development, vegetative growth, and flowering are all profoundly affected by salinity (Isayenkov and Maathuis, 2019). Several horticultural crops are affected by salt, including fruits, vegetables, and spices. Salt stress causes ionic strength imbalances, which disrupt a wide range of biochemical, physiological, and metabolic processes (Figure 6) (Mohamed et al., 2022). They include osmotic stress, water stress, oxidative stress, nutritional stress, and decreased cell division. Nanoparticles, such as zinc, silver, silicon dioxide, copper, iron, manganese, boron, cadmium, tin, titanium dioxide, cerium oxide, and potassium dioxide, were used to reduce the harmful outcomes of salt stress on plants (Zulfiqar et al., 2019). In salt-sensitive Medicago sativa, K NPs were applied topically, increasing salt tolerance by increasing proline and antioxidant-enzyme content (including catalase) (El-Sharkawy et al., 2017). Ag-NP treatment of pearl millet plants resulted in decreased MDA and ROS levels as well as improved antioxidant functioning, which may have been brought about by a decrease in Na^+ absorption in the leaves (Khan et al., 2020). Rising photosynthetic activity in Brassica napus was found to be possible with the support of cerium-oxide nanoparticles by modifying the root cells and subsequently enhancing the mineral intake (Rossi et al., 2017; Khan et al., 2020). Applying nanoparticles to plants has been shown in an increasing body of research to significantly mitigate salt stress's deleterious effects and enable the regulation of plant responses.

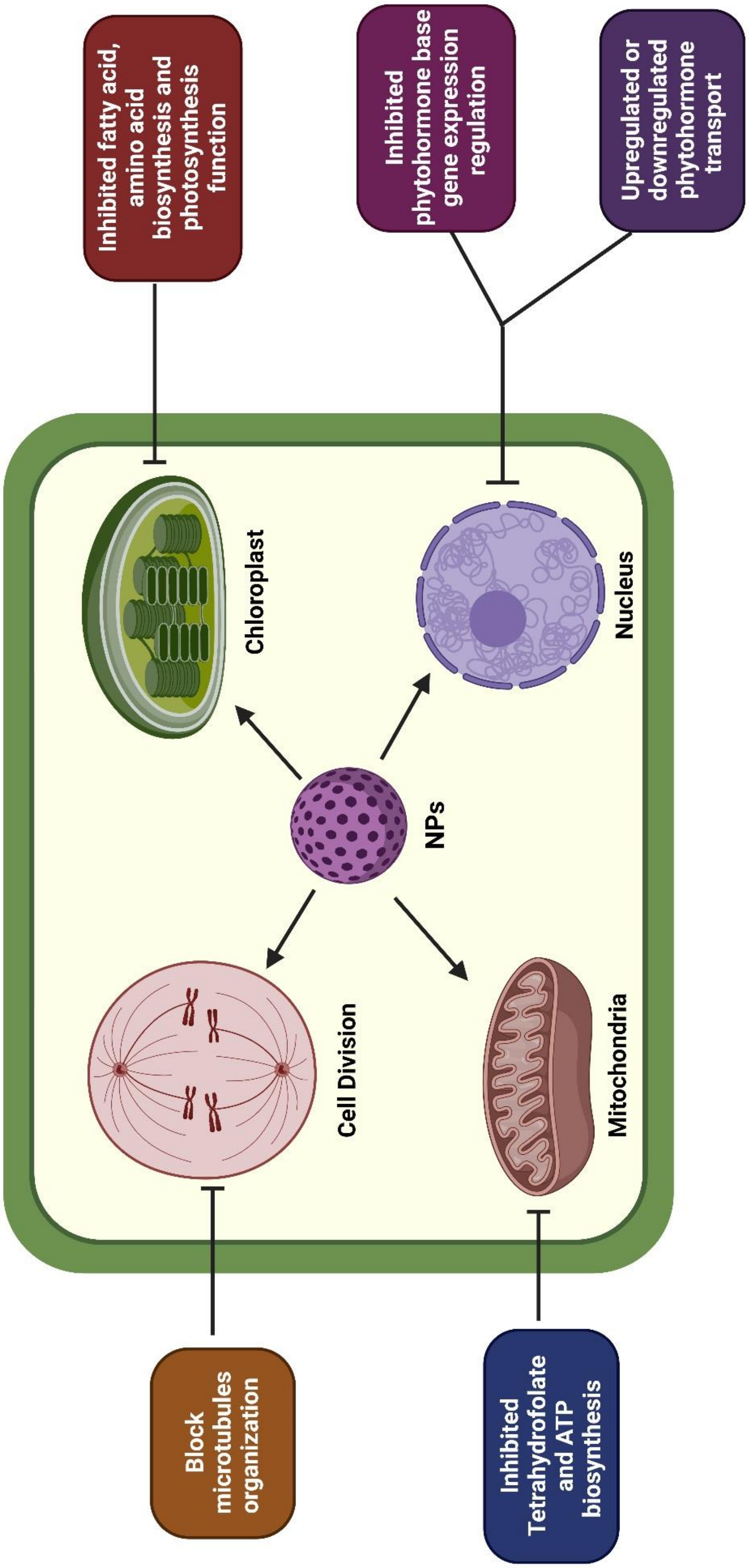

Fig. 4. Mode of action of NPs mediated nano-herbicides agents use for crop protection.

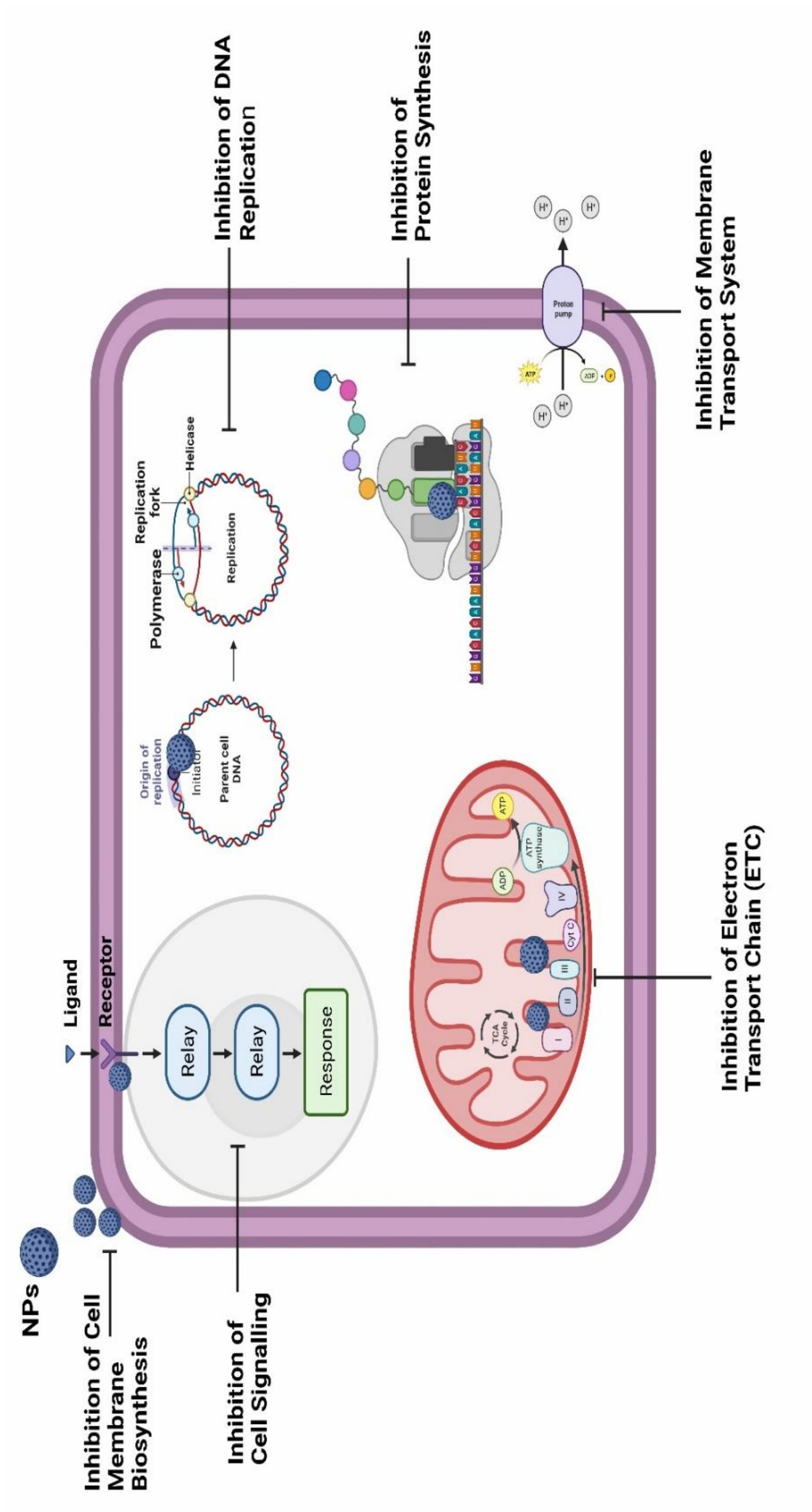

Fig. 5. Mode of action of NPs mediated nano-bactericide agents used for crop protection.

4.4.2 Drought Stress

Drought is a key environmental condition that has piqued the interest of environmental and agricultural scientists alike. The most important global agricultural problem is stunting plant development and production. Plant growth parameters are affected by drought stress, which has a ripple effect across the economy (Kumar and Verma, 2018). Crop productivity is decreased by drought more than any other environmental condition. The IPCC predicts that by 2100, global average temperatures will rise between 1.8 to 4.0 °C and that widespread drought will impact many regions (Ozturk et al., 2021). The agricultural sector is impacted by droughts when plants are unable to grow regularly and complete their life cycles due to a lack of water.

Drought conditions are made worse by the ongoing decrease in precipitation and rise in evapotranspiration demand (Farooq et al., 2012). Reduced crop yield is a direct result of water scarcity, which causes cell shrinkage, membrane disruption, oxidative stress, and leaf senescence (Figure 6) (Tiwari et al., 2016). As water is necessary for cell turgor, which is the pressure that a contained liquid exerts on cell walls to cause cells to grow larger, drought stress affects plant development (Zhang et al., 2020). Drought reduces crop yield and water efficiency due to reduced cell division and growth rates, smaller leaves, longer stems and roots, disordered stomatal oscillations, and different water and nutrient connections (Farooq et al., 2012). A previous study has shown that NPs boost drought resistance in plants by improving water absorption and root hydraulic conductance and showing the differential distribution of proteins that participate in detoxifying ROS, stress and hormone signaling, and oxidation-reduction pathways, among other morphological, physiological, and biochemical changes (Alabdallah et al., 2021).

Metabolic and physiological functions of crops under drought have been demonstrated to enhance after foliar use of metal-oxide nanoparticles like iron oxide, titanium oxide, and zinc oxide (Alabdallah et al., 2021). A rise in chemical or physical parameters, nutrient status, photosynthetic pigments (particularly those associated with fruit cracking), phenolic content, and amounts of osmolytes, antioxidant enzymes, and abscisic acid was seen after the administration of Si NPs to water shortage-stressed pomegranate plants(Zahedi et al., 2021). Green ZnO-NPs are used topically at low levels to boost tomato drought tolerance (El-Zohri et al., 2021). The impacts of drought stress on fenugreek plants were reported to be mitigated by both nano fertilizers and green-produced Fe_3O_4 NPs (Bisht et al., 2022).

The advantages of using NPs to boost plant drought tolerance may be realized only under certain climatic conditions (Potter et al., 2021). Prior research has shown that Si NPs increase plant resistance to drought stress. For instance, hawthorn plants given Si NPs showed improved drought tolerance, and alterations in defense-related physiological indicators were seen over a range of drought intensities and Si NP concentrations (Ashkavand et al., 2015). Similarly, Si NPs showed promising post-drought plant recovery capability in barley through the modulation of morpho-physiological characteristics (Ghorbanpour et al., 2020). The growth and production of cucumber were improved in water-limited and salty environments (Alsaeedi et al., 2019). Wheat plants exposed to drought were found to benefit from chitosan NPs in the form of elevated biomass, CAT and SOD functions, rate of photosynthesis, production, and relative water content (Behboudi et al., 2019). Soil treatment of CeO NPs significantly value-added plant growth at 100 mg/kg and amplified the photosynthetic rate by regulating the water use effectiveness in soybean (Glycine max) plants, while foliar application of Fe NPs was described to lighten drought stress effects on safflower cultivars (Chen et al., 2017). The use of silver NPs mitigated the negative impacts of drought on lentils (Lens culinaris Medic.) plants (Das et al., 2019). To increase drought tolerance in *Arabidopsis thaliana* abscisic acid was delivered with the help of Si NPs (Sun et al., 2017).

4.4.3 Heat Stress

Heat stress can occur in extremely hot environments. Global warming has made this trend even more severe in recent decades. It is commonly agreed that heat stress occurs when temperatures remain beyond a critical level for a prolonged period, hence instigating irreversible impairment of plant growth (Shafqat et al., 2021). The intermolecular interactions necessary for optimum growth during hot summers could be disrupted by these extreme shifts, limiting plant development and fruit set (Shafqat et al., 2021). Heat stress reduces photosynthetic efficiency and hurts plant growth, survival, and output (Figure 6) (Shafqat et al., 2021). In the tropics and subtropics, heat stress has the potential to become a major factor limiting the output of field crops. Among the many environmental stresses that are continually shifting, rising temperatures are among the most concerning (Ohama et al., 2017). Boosted reactive oxygen species (ROS) production and oxidative stress cause cell death in crop plants by damaging membrane lipids, upsetting cellular homeostasis, and slowing down a variety of metabolic processes (Effects of high temperature on malondialdehyde content, superoxide production, and changes growth in wheat seedlings (*Triticum aestivum* L.), 2010). Furthermore, heat stress disrupts photosystem II, causes chlorophyll breakdown, and reduces carbon fixation, all of which reduce photosynthesis and stunt plant development (Cao et al., 2018).

Modern nanotechnology breakthroughs have revolutionized the agricultural sector, offering the possibility of improved plant growth and development under stressful environments (Rana et al., 2021). The use of NPs to increase crop plants' resistance to heat stress has been the subject of several recent research (Pirzada et al., 2020). Application of selenium NPs increased the tomato plants' chlorophyll content, water potential, and growth rate which significantly mitigated heat stress. Similarly, the addition of TiO_2 NPs greatly decreased heat stress, as measured by a tomato plant's stomatal opening (Qi et al., 2013). Wheat growth was enhanced when the biogenic Se-NPs (100 g/ml) were applied (Haghighi et al., 2014). Similar results demonstrated that the addition of silver NPs noticeably improved the morphological characteristics of wheat plants subjected to heat stress (El-Saadony et al., 2021).

In conclusion, sustainable agriculture can benefit from increased heat stress acceptance in plants through the use of metallic NPs as nano-fertilizers. Researchers observed that by activating the antioxidant defense system, Se-NPs could mitigate the unfavorable effects of high temperatures on sorghum plants, including membrane damage, decreased pollen germination, and lower crop yields (Djanaguiraman et al., 2018a). Wheat plants treated with Ag-NPs showed improved morphological growth and were protected from heat stress (Iqbal et al., 2019). The production of antioxidant enzymes and the rate of lipid peroxidation were both shown to be increased by exposure to Zn nanoparticles in wheat, which helped the plant survive heat stress in a better way (Kim et al., 2017).

4.4.4 Flood Stress

Most plants are sensitive to flooding because too much water makes the soil soggy. Excessive precipitation, inadequate drainage, or careless watering can contribute to flooding. Complete flooding can kill plants because their roots are unable to escape the water. The availability of food and the economies of countries are both affected by flooding, which is one of several abiotic stresses. It has an effect on vegetation in various biomes, including wetland, tidal, and salt marsh areas. Wetland plant species display resistance to branch submergence and soil water logging, while dry-land plants are more vulnerable to the effects of floods.

Due to a shortage of oxygen, plant respiration is stifled as there is too much water in the air gaps between the roots (rhizosphere) and the atmosphere this is known as hypoxia. Root metabolism, nutrient uptake, and plant growth as a whole are all impacted by flooding stress, as soil pH and redox potential are altered, carbon-dioxide concentration rises, and phytotoxins are mobilized. It has been claimed that flooding stress in plants can be reduced by using nanoparticles. Soybean plants grown under flooding stress benefited from silver NPs because they reduced stress levels and promoted growth by modulating amino acid synthesis, protein synthesis, glycolysis, and wax formation (Mustafa et al., 2015, 2016). Another study looked at the influences of Al_2O_3 NPs on the growth of soybean plants that were under stress from flooding. Root length (including hypocotyl length) was increased due to Al_2O_3 NPs, and proteins involved in glycolysis were suppressed, cells entangled in scavenging reactive oxygen species were arbitrated by upregulating the ascorbate/glutathione pathway (AsA/GSH), and ribosomal proteins were risen (Mustafa and Komatsu, 2016).

4.4.5 Mode of action of NPs to mitigating abiotic stress

Nanoparticles (NPs) can alter plant metabolism through the delivery of micronutrients, the regulation of genes, and the interference with several oxidative processes (Liu and Lal, 2015). While the oxidative mechanism has been somewhat elucidated, it remains unclear how exactly NPs generate reactive oxygen species (ROS). The NPs can cause an oxidative burst and an increase in ROS levels by interfering with the electron transport chain in mitochondria and chloroplasts (Figure 6) (Tripathi et al., 2017a).

Carbon fixation slows under stress, which increases photoinhibition and may increase H_2O_2 and superoxide anion radical generation in the photosystem (Liu et al., 2021). Protein modifications, lipid peroxidation, and DNA damage are all brought on by the reactive oxygen species (ROS) produced by NPs (Adil et al., 2022). Plant interactions with NPs enhance lipid peroxidation and DNA damage. Plant cell death can occur as a result of apoptosis or necrosis brought on by an increase in reactive oxygen species. Nonetheless, ROS are involved in several biological processes, such as stress tolerance, despite their destructive tendency (Chawla et al., 2013). The damaging or signaling role of reactive oxygen species is determined by the ratio of ROS production to scavenging. The cells have refined their antioxidant function to the point that they can tightly regulate ROS levels. Antioxidants, both enzymatic (superoxide dismutase, catalase) and non-enzymatic (ascorbate, glutathione, carotenoids, tocopherols, and phenolics), are linked to plant defense systems (Demiral and Türkan, 2005).

Numerous research, among others, has shown that plants exposed to NPs create more antioxidant molecules. Phytohormones can play a part in plant stress response signaling (Raghavendra et al., 2010). Plant hormones are naturally occurring chemicals that affect growth, development, and stress resistance in plants (Raghavendra et al., 2010). Several hormonal pathways can be stimulated or inhibited in response to abiotic challenges (Nadarajah, 2020). Stress from Ag NPs led to an increase in cytokinin levels in red pepper (Capsicum annuum), while CuO NPs caused auxin and ABA levels in cotton to drop (Bhatla and A. Lal, 2018; Vissenberg et al., 2020). This evidence points to NPs affecting the hormonal equilibrium and metabolism of plants. Numerous investigations have shown that NPs can also impact the content and activity of photosynthetic pigments in plants (Tripathi et al., 2017a). Plants exposed to high levels of NPs experience stunted growth or even death as a result of the particles' interference with photosynthesis (Tripathi et al., 2017a).

4.5 Nano-biosensors

4.5.1 Nanopore DNA Sequencing

More than 40 years into its existence, DNA sequencing technology has evolved to allow for greater data collection at an ever-increasing rate (Dumschott et al., 2020). With the publication of the bacteriophage X174 genome sequence by Sanger and Coulson in 1977, first-generation sequencing has officially begun (Sanger et al., 1977). First-generation sequencing was the standard in the area until the establishment of high-throughput sequencing technology in the middle of the 2000s. Large-scale sequencing programs were contested by 2nd generation sequencing methods despite their shorter maximum read lengths compared to Sanger sequencing (Lu et al., 2016; Dumschott et al., 2020). It has been noted, however, that when big, highly repetitive genomes are assembled de novo, the short reads acquired by these second-generation sequencing technologies often lead to poor assemblies (Lu et al., 2016).

The study of simple genomes, resequencing, and RNA sequencing all continue to make extensive use of these methods. Recent advances in sequencing technology have made it conceivable to extract substantially longer reads, while still generating data at rates that are on par with or quicker than Ist generation approaches. Third-generation technologies have advanced to the point that single DNA molecules can be sequenced in real-time, with read lengths that can reach several kilobases (Figure 7). By covering the extensive repetitive regions of complicated genomes, these reads help improve sequence assemblies (Lu et al., 2016). Pacific Biosciences (PacBio) was the first to employ single-molecule real-time sequencing to sequence plant genomes (Vanburen et al., 2015). This began being tracked with the help of Oxford Nanopore Technologies (ONT) in 2014.

Nanopore sequencing technologies have become increasingly important in recent years for identifying plant pathogens. Researchers have produced a standard technique for identifying several plant infections (bacteria, viruses, fungus, and phytoplasma) operating a handheld sequencing machine built by Oxford Nanopore Technologies (called "MinION") (Figure 7) (Chalupowicz et al., 2019). Results from assays can be interpreted similarly to those from longer-standing diagnostic techniques (such as polymerase chain reaction (PCR) and enzyme-linked immunosorbent assay (ELISA) (Chalupowicz et al., 2019). Researchers were able to discover *Candidatus Liberibacter asiaticus* and plum pox virus in peaches within 24 hours using nanopore sequencing and whole transcriptome amplification (Badial et al., 2018). Predicting the presence of multiple plant virus species in a water yam plant allowed us to employ MinION for extensive genome mapping. Dioscorea bacilliform virus, Yam mild mosaic virus, and Yam chlorotic necrosis virus were some of the viruses identified (Filloux et al., 2018). Nanopore technology advancements will allow for the expansion of more efficient sequencing programs despite limitations of existing equipment, such as a lack of discrimination between sequences with identical characteristics and a high per-read error rate.

4.5.2 Nano biosensors

Nano biosensors have found several uses in agriculture, from nutrient monitoring, pesticide, and herbicide detection, and insecticide efficacy to soil moisture and pH analysis. The modestly deployed biosensors can boost agricultural yields, which is beneficial for sustainable agriculture (Rai et al., 2012). Precision farming, which utilizes modern sensors, offers the potential to boost yield by allowing more effective fertilizer management, reduced input costs, and fewer environmental issues. Nano-sensor-based smart delivery systems could improve the efficiency of water, fertilizers, and agrochemicals in precision agriculture. Plant viruses, the concentration of soil nutrients, and crop diseases can all be spotted by nano-sensors (Rai et al., 2012). Nano-sensing of the acetolactate synthase inhibitor metsulfuron-methyl was achieved by utilizing an atomic force microscope tip that has been functionalized with the enzyme (Otles and Yalcin, 2010). Food safety is enhanced as a result of the employment of bio-nano sensors, which enable the speedy detection of bacteria and viruses and their accurate quantification (Hossain et al., 2015). The direct examination of vegetable samples has been facilitated by a highly sensitive biosensor for organophosphorus pesticides, which was developed by functionalizing carbon nanotube surfaces with amino groups to regulate the competent immobilization of acetylcholinesterase onto a glassy carbon electrode (Yan et al., 2013). Researchers have developed a multiwall carbon nanotube biosensor constructed using liposome bioreactors, which detects the presence of acetylcholinesterase, allowing the recognition of organophosphate pesticides (Sun et al., 2013). The biosensor detects both pesticides with a sensitivity of 19031012 mol/dm3 by measuring minute changes in local pH around an electrode surface caused by the suppression of an acetylcholinesterase-acetylcholine enzyme interaction (Viswanathan et al., 2009). Single-walled carbon nanotubes (SWCNTs) that function electrochemically can be used as nano-sensors for gases like ammonia, nitrogen oxides, hydrogen sulfide, sulfur dioxide, and volatile organics, which could be useful for censoring these pollutants in agriculture, studying their effects on the living matter or human health, and encouraging higher crop yields (Kah et al., 2019). High-sensitivity (1.0 mol/dm^3) screening of organophosphorus compounds using fluorescence spectroscopy and gold nanoparticles has been reported (Dasary et al., 2008).

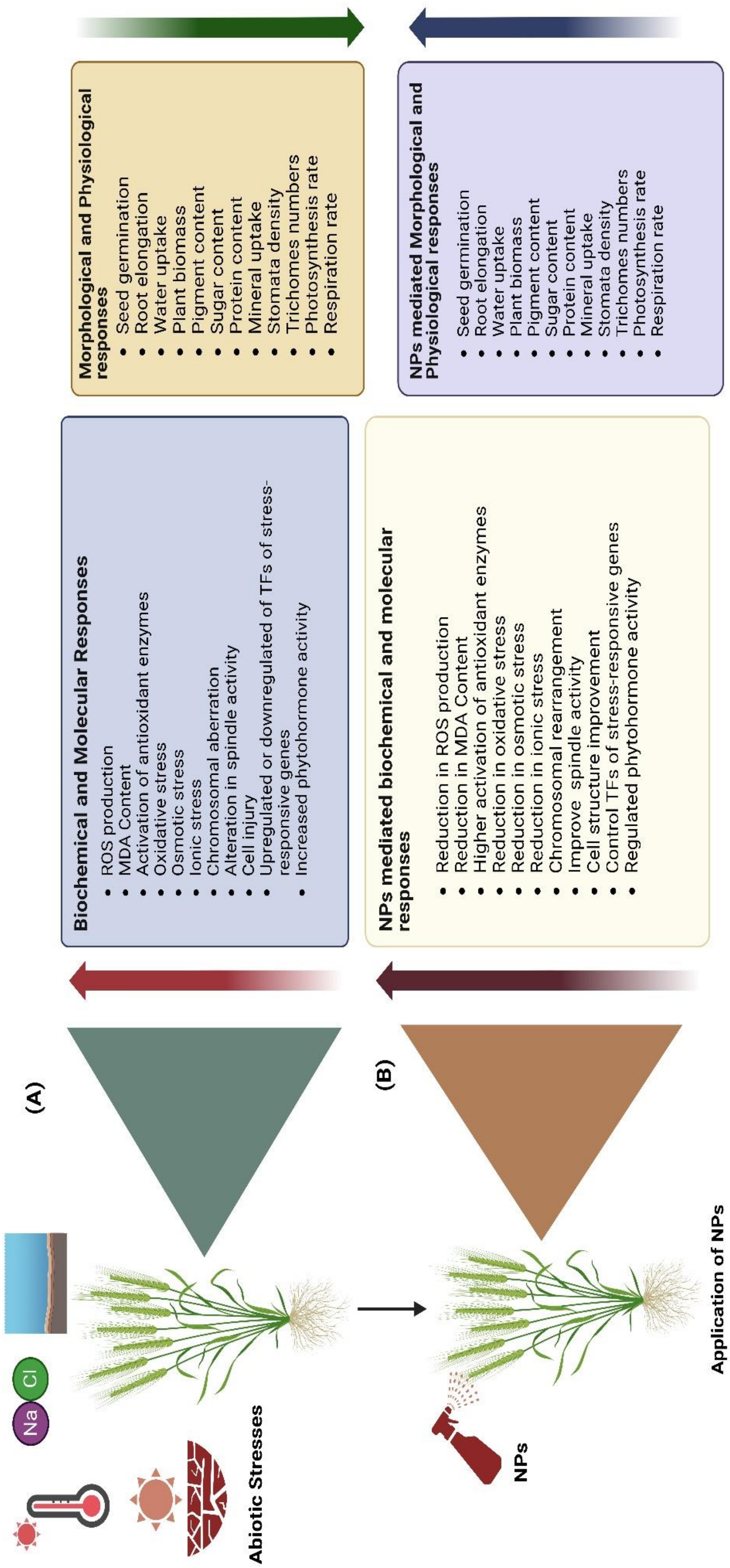

Fig. 6: Effect of abiotic stresses on plants and application of NPs for mitigation of abiotic stresses.

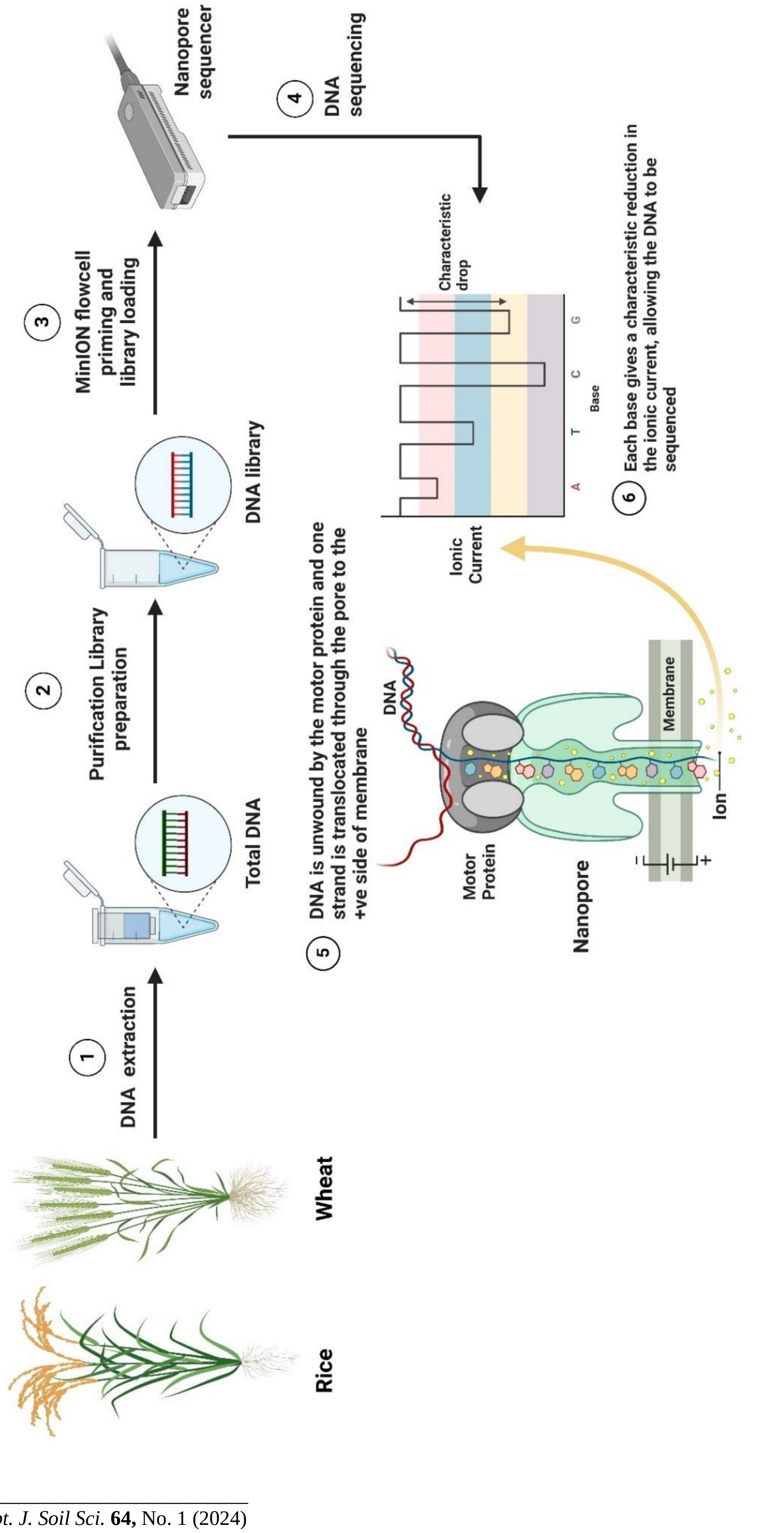

Fig. 7. Diagrammatic repreparation nanopore mediated DNA sequencing of different crops.

4.5.3 Nano barcode

Nano barcode particles are constructed using a semi-automated, highly scalable technique that involves electroplating inert metals like gold, silver, etc., into templates that define particle diameter, leading to in a discharge of nanorods from the templates. Multiplexed gene expression analysis relies on these nano barcodes as identifiers. Improved plant resistance to drought, salt, and disease is one result of the integration of nanotechnology and biotechnology. Nanotechnology-based gene sequencing makes it possible to rapidly and cheaply identify and employ plant gene trait resources (Branton et al., 2008).

4.5.4 Soil Nano-sensors

Soil is essential to plant life because it provides a steady supply of nutrients. The transformation of contaminants is just one of the main ecologically significant activities that take place in the soil. Water, pH, organic matter, and pollution levels are just a few of the markers used to gauge soil quality. Pollutant identification is crucial since these contaminants not only reduce plant growth and crop productivity but also increase the food chain's contamination by being absorbed by crops.

Soil pollutant levels are typically determined using chromatography, electrochemical detection, mass spectroscopy, etc., following the standard protocol of field sampling, plant tissue digestion, extraction, sample purification, etc (Mao et al., 2020). Sampling is a laborious and time-consuming process that calls for sophisticated equipment and expert handling. In addition, it is impossible to do such monitoring in real-time and on-site. In light of the foregoing, a trustworthy technology is required to accomplish rapid, on-site, and real-time assessment of soil contaminants. A new form of plant nano-bionic sensor was developed in a study to selectively monitor soil arsenic levels (Lew et al., 2021).

Humans and ecosystems are in grave danger from arsenic and its compounds. Here, self-powered detectors made from specially developed nanomaterials are interfaced with plants. The scientists developed a non-destructive way to monitor the internal dynamics of plants as they absorb arsenic from the soil by using SWCNTs-based near-infrared (NIR) fluorescence nano-sensors that are placed in plant tissues. When compared to conventional methods, the plant nano-bionic strategy of embedding optical nano-sensors within living plants is a major advancement. This new nano-bionic sensor type will be crucial in the monitoring of soil quality in the future and will inspire the development of further nano-sensors for soil condition detection. Portable and low-cost electronic equipment combined with living plants will provide accurate soil quality evaluation in real-time and on-site.

4.5.5 Metal ion detectors Nano-sensors

Plants rely on metal ions for signaling, particularly calcium, potassium, sodium, and magnesium ions. In response to various stimuli, plant physiological changes can be reflected in transitory increases, waves, and oscillations of metal ions (Morandi et al., 2007). It is also crucial to observe shifts in intracellular metal ion concentrations when assessing plant nutrition (Choi et al., 2017). This highlights the need to investigate the dynamic variations of metal ions in plants (Choi et al., 2017). Building an ion-selective microelectrode is the mainstay of plant-based metal ion detection technology.

Metal ion fluxes in a plant’s root elongation zone or suspension cell can be measured non-destructively with this approach. The detecting method is sophisticated though, and calls for the utmost accuracy. Consequently, it is important to create a quick and easy technique. To do this, Janni et al. developed a bioreactor—an *in vivo* organic electrochemical transistor sensor based on poly(3,4-ethylene dioxythiophene): poly(styrene sulfonate)—to detect variations in the quantities of metal ions (Na^+, K^+, Ca^{2+}, and Mg^{2+}) in the sap of drought-stressed tomato plants (Janni et al., 2019). After 30 hours without water, the concentration of metal ions steadily enlarges, as shown by the device that was incorporated into the stem and realized continuous monitoring of the plant’s physiological status. To improve tomato varieties that can withstand drought, this gadget can be very helpful. Since this device is implanted directly into the plant’s stem, more research is required to determine its long-term stability and biocompatibility as well as the interaction mechanism between the nanomaterials employed and the plant system. In addition, data transmission is still done through the wire, which is incredibly cumbersome for long-term use and highlights the necessity for future integration with wireless devices.

4.5.6 ROS detectors Nano-sensors

Superoxide anion, hydrogen peroxide, carboxyl radical, nitric oxide, etc. are all examples of reactive oxygen species (ROS) that play important roles in signal transmission in a wide range of organisms. Reactive oxygen species (ROS) evolved from harmful waste products of aerobic metabolism and now play critical functions in the intricate cellular communication network (Mittler et al., 2011). It is well established that reactive oxygen species (ROS) emission is a common and rapid plant defense mechanism in response to pathogen interactions and environmental challenges (Mittler et al., 2011).

Transducing hormone signals and controlling the building of cell wall polymers are two examples through which ROS have been recognized as crucial growth regulators in plants (Muller et al., 2009). Consequently, it is crucial to investigate ROS generation and intercellular activities during plant development. The fluorescent probe is the most popular method used to track H_2O_2 levels in plant leaves, while other methods have also been developed. Yet, the time and effort required by conventional fluorescence probe technology for isolating plant samples are less. Hence, electrochemical approaches with the benefits of simplicity, cheap cost, and high sensitivity have been widely utilized in the study of plant biochemical processes before the introduction of superior H_2O_2 fluorescence detection technologies in plants. To electrochemically *vivo* monitor the changes in H_2O_2 levels in aloe leaves under salt stress, Ren and coworkers used hemoglobin (Hb) and SWCNTs modified carbon fiber ultramicroelectrode (Hb/SWCNTs/CFUME) (Ren et al., 2013). Due to the catalytic impact of Hb on the decrease of H_2O_2, amperometric *in vivo* monitoring of H_2O_2 was achieved by inserting Hb/SWCNTs/CFUME into the leaf's central vein. Lima et al., employing a platinum (Pt) disc microelectrode, performed in situ monitoring of H_2O_2 generated in *A. tequilana* leaves following bacterial inoculation (Lima et al., 2018).

The electrochemical data showed that H_2O_2 was produced in proportion to the number of inoculated leaves. A very sensitive ROS electrochemical nano-sensor was also developed. Electrodes with outstanding catalytic activity were spontaneously deposited on ultrathin metallic molybdenum disulfide (MoS2) nanosheets employed in the fabrication of a freestanding paper electrode. Advantages such as portability, high selectivity and stability, and a broad linear range were shown by the flexible nanosensor in its monitoring of H_2O_2 in aloe plant extract. These electrochemical nanosensors enable high selectivity and stability in real-time monitoring in the field, doing away with the need for laborious data processing in the process. Unfortunately, most of these studies are conducted in a lab, and these nanosensors' biocompatibility has not been thoroughly tested. In addition, a highly integrated, miniaturized, and portable monitoring system requires the development of electrochemical nanosensors that can realize in situ monitoring on living plants and can be coupled with wireless devices.

4.5.7 Phytohormone Detectors Nanosensors

Many different types of hormones, such as auxins, gibberellins, abscisic acid, cytokinins, salicylic acid, ethylene, and peptide hormones, are produced by plants. These are very small organic molecules or active chemicals that govern physiological responses in plants and are induced by plant cells in response to particular environmental signals. They are thus crucial in the process of plant adaptation to different stressors (Fahad et al., 2014). High-performance liquid chromatography, gas chromatography-mass spectrometry, fluorescence spectrometry, and capillary electrophoresis (CE), have all been employed to detect plant hormones (Chen et al., 2011; Lima et al., 2018). Nevertheless, their only application is *in vitro*, where extensive preparation of plant samples is required.

Hormones can also be detected in living plants with the help of optical nanosensors. With their strong fluorescence, broad excitation spectrum, adjustable emissions, and outstanding photostability, QDs have found widespread application as bio-labels and bioimaging probes (Chen et al., 2014). Furthermore, aptamers and other target-specific ligands can be conjugated to QDs to provide more targeted molecular imaging. The aptamer-functionalized QDs (zinc ion (Zn^{2+}) doped cadmium telluride) were used to create a fluorescent aptasensor for *in vivo* detection of tomato systemin (TomSys), a type of peptide hormones in plants (Liu et al., 2015). The results demonstrated that the fluorescence was suppressed due to the non-covalent contacts between aptamer-functionalized QDs on the surface of GO nanosheets in the absence of TomSys. Because the aptamer-functionalized QDs were released from the GO surface in the presence of TomSys, the fluorescence of the QDs returned. Fluorescent nanosensors based on metals have also been developed extensively for tracking signaling molecules (Figueroa et al., 2013).

For the selective and sensitive *in vivo* detection of salicylic acid, Chen et al. (Chen et al., 2020a) created a curcumin-Cu ion (Cu^{2+}) based fluorescent nanosensor. The results demonstrated that Cu^{2+} was initially chosen to bind the diketone portion of curcumin, leading to the paramagnetic "turn-off" of curcumin's luminous properties. The salicylic acid was then added, and a highly selective "turn-on" pattern of fluorescence towards Cu^{2+} was seen. These fluorescence nanosensors outperform electrochemical nanosensors in terms of selectivity and sensitivity, and the detection process may be visualized more intuitively because of the fluorescence signal's complex variations. Nonetheless, the above-mentioned issues with optical sensors highlight the continued need for research into their long-term durability and biocompatibility in plants.

5. Concern about NP phytotoxicity

The term "nanotoxicity" describes the risk that nanoparticles pose to living things. Inflammation, oxidative stress, and damage to DNA or cellular structures are some of the ways it can affect human health and agricultural yields. In agriculture, nanoparticles can originate from both natural and anthropogenic (man-made) sources. Volcanic eruptions, forest fires, and the weathering of rocks and minerals are all natural sources of nanoparticles in agricultural settings. Natural nanoparticles released by these processes can be taken up by living things like plants and animals. Nanomaterials used in pesticides, fertilizers, and other agricultural products are one human-made source of nanoparticles in food production.

Manufacturing and mining are two examples of industrial processes that can release nanoparticles into the environment. While nanotechnology has the potential to enhance farming methods, there are valid worries about the long-term effects of using nanomaterials in food production on human and environmental health. As a result, it is essential, before widespread adoption, to thoroughly assess the risks and benefits of using nanomaterials in agriculture. Different countries and regions have different rules regarding the use of nanoparticles in farming. The US Department of Agriculture (USDA) oversees the application of nanotechnology in food and agriculture, while the Environmental Protection Agency (EPA) regulates the use of pesticides containing nanoscale materials.

Risk analysis and nanotoxicological evaluations are prerequisites for the successful commercial use of NPs and will influence how safe NPs are developed in the future (Natasha et al., 2022). Although toxicological evidence is needed to support this claim, nanostructures are thought to be more toxic than their non-nano counterparts (Figure 8) (Lee et al., 2010). To control how NP's interaction with the environment and biological systems affect toxicology, logical science-based management strategies must be developed (Khan et al., 2021). It is evident that biogenic NPs PC (protein corona) present around the NP surface mediates and regulates NP interactions with living systems or cells, which may result in cytotoxic, genotoxic, and pathophysiological effects if the NP interaction with the cell is incompatible (Thakkar et al., 2010).

The PC can play a beneficial or detrimental role in terms of biocompatibility depending on the various factors influencing the interaction, like the type of protein that makes up the PC, hydrodynamic size, and any associated charges that can increase or decrease NP toxicity. The morphological and physiological effects of NPs' phytotoxic effects can be seen in chlorophyll damage, damaged root tips, decreased root length, reduced biomass, and other formative oxidative damage-related alterations. However, not all NPs operate in this manner. For instance, ZnO-NPs in Pisum sativum and Ag NPs in Solanum lycopersicum decreased the amount of chlorophyll, whereas TiO_2 NPs in *Cucumis sativus* and ZnO NPs in *Cyamopsis tetragonoloba* increased the amount of chlorophyll (Judy et al., 2012; Mukherjee et al., 2013; Song et al., 2013).In response to NP penetration, biological systems frequently produce reactive oxygen species (ROS), that can impair normal biophysical, biochemical, and abiotic-stress-related activities as well as the regulation of genes involved in stress resistance, causing NP- NP-specific genotoxic impacts (Hosseinpour et al., 2020). Due to abnormalities and oxidative stress in cell membranes brought on by ROS-induced lipid degeneration, NP penetration causes ROS to produce additional toxic impacts like cell death and leakage of ions. Due to ion leakage in the cells, CeO_2 NPs in *Zea mays* caused lipid peroxidation, but *Oryza sativa* did not exhibit the same effect at the same NP concentration (0-500 mg/L) (Sanzari et al., 2019).

Plant-NP interactions have the potential to negatively impact secondary plant metabolism, hormonal homeostasis, and plant growth and development. NP exposure suppressed the expression of specific genes linked to phosphate loss, pathogens, and stress response, which may have hurt plant defense mechanisms and root development, according to a recent transcriptome analysis of *Arabidopsis thaliana* (Sanzari et al., 2019). Nutrient distribution can be disrupted by NPs, which has an impact on healthy growth and development. CeO_2 NPs prevented rhizobacteria from fixing N_2 for use by soybean plants, reducing the amount of N available to the plant and impairing normal growth and function (Priester et al., 2012; Schwabe et al., 2013). In contrast, P and K were made more accessible by TiO_2 NPs in *Cucumis sativus*. 500 mg/kg of treatment on plants resulted in 35% more K and 34% more P (Servin et al., 2013). In addition, some nanomaterials, like TiO_2, are resistant, and over time, the metal component may accumulate in the environment. Furthermore, the constant application of nutrients like copper eventually results in an excess of nutrients in the soil, which can be harmful to plants. The upregulation of antioxidant compounds and downregulation of genes encoding for metal transport are two potential mitigation strategies for NP stress (Taylor et al., 2014).

Metal NPs induce a generalized stress response, primarily the oxidative stress response, according to a recent study that used omics data in a systems biology approach in plant varieties like rice, tobacco, and wheat (Ruotolo et al., 2018). This implies that parts of NP phytotoxicity must be discovered by high-throughput investigations of genetic and metabolic processes that are brought on by NP exposure, even if no toxic effect is shown at the phenotypic level **(Figure 8 B)** (Majumdar et al., 2015). It is uncertain if the kind of NP and its interaction particularly affect nanotoxicity or whether the detoxification systems that are activated in response to NP stress are capable of alleviating the stress at the biomolecular scale. Understanding the properties of synthesized NPs is crucial before examining their effects on plant systems to reduce any dangers (both human and environmental) connected with their applications and other functions (Pradhan and Mailapalli, 2017). Proteomic studies that identify protein markers will shed light on the toxicities brought on by NPs at the proteome level. Before any nano agriproducts are put on the market, extensive *in vivo* and *in vitro* phytological testing is necessary to guarantee efficient nutrient utilization with minimal to no associated toxicity (Pradhan and Mailapalli, 2017).

6. Agri-Nano-enabled products and marketing approaches for sustainable agriculture

The term "industrial agriculture" refers to the complex network of systems that together generate the global food supply. Nanotechnology's rapidly growing consumer markets have opened up new opportunities for the agricultural industry to profit from high-end goods. Even though there is plenty of food in the modern world, many people still go hungry every day due to environmental factors. The purpose of breeding drought- and pest-resistant crops is to boost harvests. The NPD database details 243 agricultural nanoproducts currently available. Some 243 unique agricultural nanoproducts are being introduced to consumers all over the world by 87 companies with headquarters in 28 different countries (**Figure 9**).

Animal farming, fertilizers, plant breeding, plant protection, and soil enhancement are just some of the subsets that can be created from these goods. Fertilizers, chelates, and nutrients see consistent updates from manufacturers. Commercially available product categories include precursors, chemicals, and boosters (e.g., controlled-release nanocomposites) used in the formulation of fertilizers, as well as plant growth regulators, seed speeds, hormones, and fruit enhancers. Recently, nanotechnology-based soil enhancers have received a lot of interest. Chemicals used to treat plants, such as pesticides, fungicides, biocides, and disinfectants, are the mainstay of plant protection. Stretch films made from nano-sized polyethylene have recently been used to protect hay from damaging sunlight and severe weather. Animal husbandry necessitates the use of various dietary supplements, nutrients, feed additives, enzymes, and disinfectants. Veterinary pharmaceuticals, vaccines, and wound care products are also available. Tools that help in aquaculture include oxygen and carbon dioxide level controls and fish counters. Nanotechnology has the potential to revolutionize farming by improving disease diagnosis, boosting plant nutrient absorption, cutting down on fertilizer waste, and increasing crop yields.

Silver nanoparticles, titanium dioxide nanoparticles, silicon dioxide nanoparticles, and zinc oxide nanoparticles are the most frequently reported nanomaterials in agriculture; these are used to improve plant foliage, increase stress tolerance, lengthen the shelf life of products, and increase the efficacy of soil nutrients, all of which have their own unique chemical, physical, and mechanical properties. Nano-capsules containing magnesium, manganese, iron, and potassium all play important roles in this sector. Zeolites and other porous materials can also improve agricultural output and animal well-being. There may be hundreds of nanotechnology-based agricultural producers at present, but only a select few can be called true market leaders. Some examples of such businesses include Neufarm GmbH, Plant Vitality Ltd, Kanak Biotech, FRAmelco, Aqua-Yield Hub, Organic Fertilizing, Reed Mariculture Inc, Prodotti Arca S.r.l., Kimitec Group, Richfield Fertilizers Pvt., Blue Planet Environmental, Danaflex Nano, Bioteksa, AgriLife, NanoLandBaltic, Vive Crop Protection, DVS BioLife Ltd, Samarita From our data, we can infer that the countries of India, Germany, the United Kingdom, the United States, Vietnam, Taiwan, Brazil, China, Malaysia, and the Netherlands are among the most supportive of manufacturing sympathy for putting nanotechnology's benefits to use in agriculture.

7. Future Suggestions

7.1 Future of nanotechnology in agriculture and plant science

Agriculture has made significant strides in developing and applying nanotechnology, which is the creation and modulation of matter on length scales with at least one dimension at the nanoscale, to increase plant growth and yield. Micro-nano scale dynamic monitoring of plant growth processes, pest management, fostering plant transformation, protecting the environment, and increasing plants' potential to harvest environmental micro-energy are all examples. Understanding "plant nanoscience" in depth reveals many unforeseen advantages of these nanotechnologies. There are, however, many obstacles that must be overcome in the future. These include, but are not limited to, a unified international standard, fragmented policy, nano-safety concerns, growers' health, public acceptance, "real world" application, etc. As was previously stated, there has been a rise in the number of scholarly works and patents involving nanotechnology in farming. Many factors, such as varying national legislative frameworks, limited regulation, a lack of public licensing initiatives, etc., have delayed the availability of commercial products and the results of large-scale scientific research.

The direct/indirect and cumulative effects of nanomaterials are difficult to predict because of the many ways in which their physicochemical and biological properties differ from those of individual atoms, molecules, or bulk materials. More importantly, it is still unclear how nanomaterials move throughout the environment, organisms, and humans. These issues make it very difficult to create uniform policies and laws on a global scale. As a result, there is an urgent need for collaboration between international and national organizations, as well as a massive amount of research and fieldwork. Only by banding together can we hope to overcome the obstacles presented by inconsistent policies and regulations and realize the full potential of nanotechnologies in agricultural settings. There is a gap between existing studies on the hazards of nanomaterials to human and environmental health and the complexity of agricultural ecosystems where their use may represent a significant risk of exposure. For carbon nanotubes (CNTs), graphene (graphene), metal nanoparticles (NPs), zero-valent iron (ZVI), and the other nanomaterials mentioned above, these applications include regulating the spread of agrochemicals, directing the transport of biological molecules, cleaning up polluted areas, and more. There has not been enough investigation into the specific interaction mechanism between them and the target, particularly the complex plant system. These applications will further complicate the already complex risk and exposure landscape. As a result, nano-safety concerns must be taken into account whenever possible.

Natural materials that provide minimal to no risk to growers' or customers' health should be given careful attention during the experimental design phase. Then, it's important to thoroughly examine how unique nanomaterial properties (like shape, size, and charge) affect the interaction with various plants. Finally, to evaluate risks, it is important to know how nanomaterials behave and where they end up in the environment. These nanotechnologies are still primary in the research stage, displaying advantages that are distinct from those of more conventional agricultural technologies. The aforementioned findings have been confirmed numerous times in the lab, but there are almost no examples of successful field implementation or commercialization. Additionally, studies of plant systems typically build off of other studies or observations, such as those of animals. It is possible that these studies only demonstrate their great capacity and have an effect when applied to plant systems.

Metal NPs, nano-chitosan, nano-zeolite, and other NPs have been found to improve absorption efficiency and target active chemicals to specific plant cell compartments and organelles. They still require to be meticulously planned out for various soil types and plant types, and a unified concentration standard needs to be formulated. Increasing the distribution of nanomaterials in different field experiments is also crucial. There must be a speedy transition from the lab to the field. However, to draw broad rules demonstrating that these nanomaterials are helpful to plant growth and do not endanger animal or human health, prolonged experimental observations are required. From the early stages of research to the point where it can be used in commercial applications—taking into account factors like safety, cost, marketability, etc.—takes time. Public opinion and support are crucial to the long-term success of agricultural nanotechnologies. Many people still refuse to buy foods that have been genetically modified or that have used nanotechnology.

As a result, consumers may better understand the production and application of these nanomaterials if they are included in the process itself. And people need to hear the honest and unbiased findings of field trials. More research on the risks and benefits of using nanomaterials in food production and information on how people feel about using them is required. Let the public accept food made with nanotechnology by providing thorough explanations of nano-safety issues so that people can make informed decisions. Nanotechnology's potential to boost agricultural output hinges on solving these problems. It will be important to build on past research into plant-nanomaterial interactions in the future. The term "plant nano bionics" was coined in 2014 by Strano's research group to describe the potential for new and improved functions to be conferred upon plant organelles at the interface between these organelles and non-biological nanostructures. However, SWCNTs are injected into plants via the leaves to perform these tasks. Whether or not it will eventually be possible to realize the symbiosis between nanomaterials and plants, in which nanomaterials are present initially in plant life and vanish when plant life ends. This could lead to a new definition of "plant nano bionics" and a fresh focus for "plant nanoscience" studies.

Therefore, these nanomaterials may intuitively reflect how plants interpret environmental signals for their survival, how environmental signals govern and influence plant physiology, development, and morphogenesis, and how plant cells control expression by integrating internal and external elements. These nanomaterials confer non-native functions on plants, and their dynamic changes are observable through optical or electrical techniques, reflecting the signaling pathways of plant cells indirectly. This allows for timely interventions that boost plant growth and yield. In addition to being completely safe for animals and humans, these nanomaterials do not affect plant life.

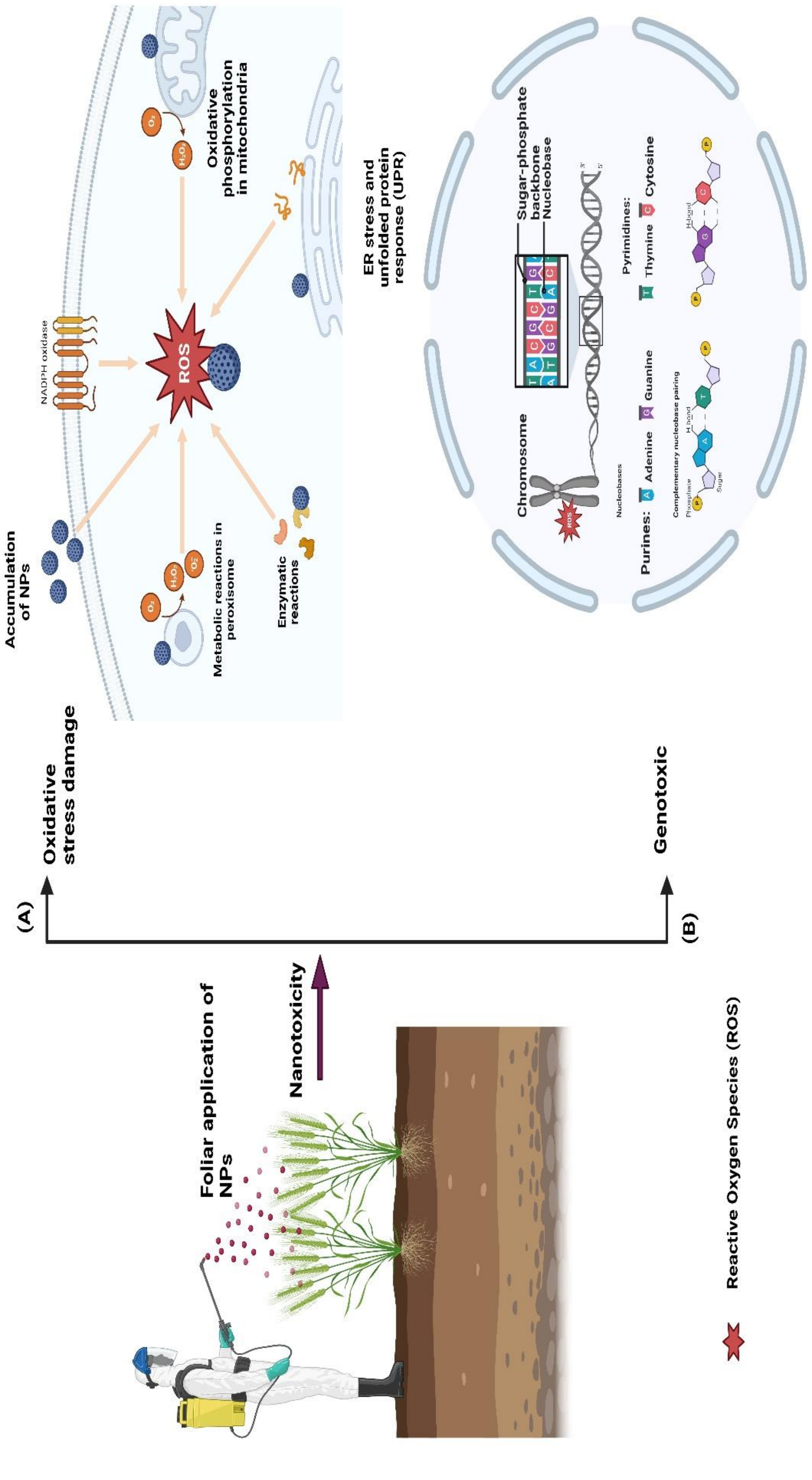

Fig. 8. Mode of action NPs mediated phytotoxicity that induced (A) oxidative stress that affected various cellular organelles and biological processes also (B) genotoxic mediated damage of genetic materials that affected molecular processes.

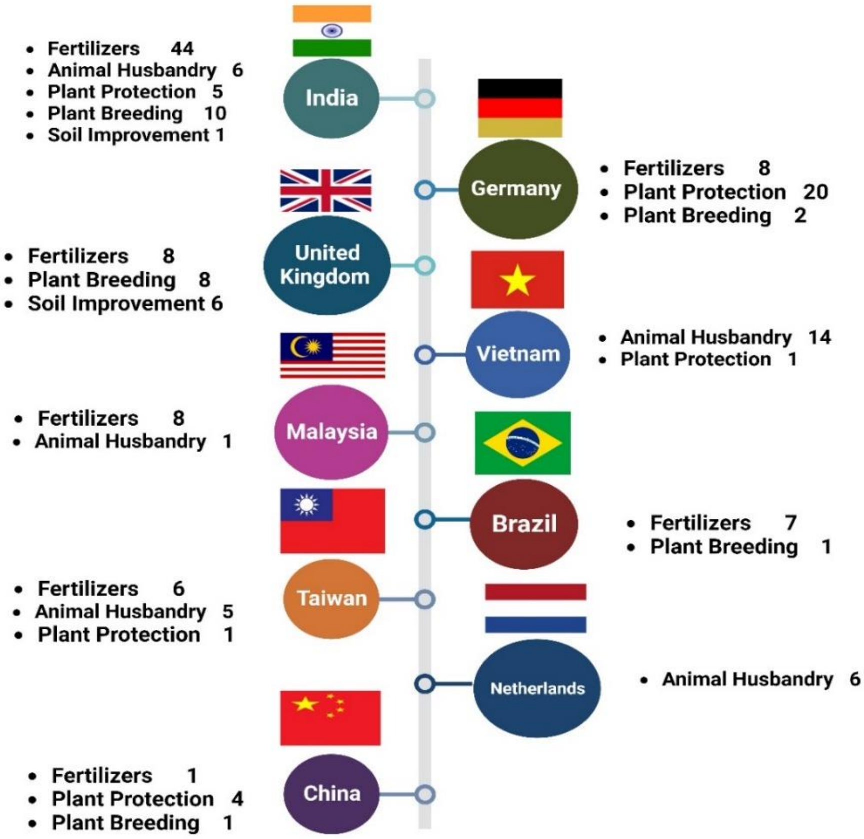

Fig. 9. Various Agri-nanotechnological products produced by various countries world-wide.

7.2 Combination of Biochar and NPs for Sustainable Agriculture in the Climate Change Era

The combination of biochar and NPs has shown the potential to mitigate plants' abiotic stress. Abiotic stress factors, such as drought, salinity, and heavy metal contamination, can significantly impact crop growth and productivity (Murtaza et al., 2023). The synergistic application of biochar and nanoparticles offers several advantages in dealing with these stressors (Elshony et al., 2019):

***(A) Water Management under Drought Stress*:** Biochar's ability to improve water retention in the soil, combined with nanoparticles designed for efficient water use, can alleviate the negative effects of drought stress on plants. The enhanced water-holding capacity of the soil helps plants maintain hydration during dry periods, promoting better growth and resilience.

(B) Salinity Tolerance: NPs can be engineered to address salinity stress by promoting ion balance in plant cells. When integrated with biochar, which can reduce the impact of salt stress on soil structure, this combination helps create a more favorable environment for plants in saline soils.

(C) Heavy Metal Remediation: Biochar has been recognized for its capacity to adsorb heavy metals, preventing their uptake by plants and mitigating the toxic effects of metal stress. The addition of nanoparticles with specific metal-binding properties can enhance this remediation process, offering a comprehensive solution for soils contaminated with heavy metals.

***(D) Improved Nutrient Uptake*:** Nanoparticles can be tailored to enhance plants' availability and uptake of essential nutrients. In combination with biochar, which acts as a nutrient reservoir and facilitates nutrient cycling in the soil, this integration aids in maintaining adequate nutrient levels for plants even under stressful conditions.

(E) Oxidative Stress Management: Abiotic stress often generates ROS in plants, causing oxidative stress. Nanoparticles with antioxidant properties can help mitigate this stress, and when coupled with biochar, which can also contribute to reducing oxidative stress, the combined effect becomes more potent.

It's important to note that the effectiveness of the combination of biochar and nanoparticles in addressing abiotic stress may vary based on the specific stress factor, soil type, and plant species. Additionally, research is ongoing to understand the long-term impacts and potential risks associated with the use of nanoparticles in agriculture.

8. Conclusion

In conclusion, the incorporation of nanotechnology into agriculture presents a groundbreaking approach to revolutionize crop production. Current applications, including NPs and precision agriculture, have demonstrated tangible benefits for sustainable farming. Advances in combining NPs with traditional inputs, such as biochar, show promise in enhancing soil health and nutrient availability. Future frontiers hold exciting possibilities, from nanosensors for real-time crop monitoring to nanorobotics for precise nutrient delivery. However, responsible research and regulatory measures are crucial to address potential environmental and health concerns. The nanoscale wonders in agriculture signify a transformative journey toward more resilient and sustainable farming practices.

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and materials: Not applicable.

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