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Green Nanofertilizers – The Need for Modern Agriculture, Intelligent, and Environmentally-Friendly Approaches

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ABSTRACT

The distinctive qualities and wide array of possible applications of nanotechnology have garnered considerable attention. Nanotechnology offers a groundbreaking way for expanding agricultural output that is also ecologically benign, helpful to living things, and economically priced—all without losing quality. There is a growing trend towards using eco-friendly technologies as substitutes for conventional agricultural inputs, such as fertilizers and insecticides. With the aid of nanotechnology, the confines of conventional farming techniques can be overcome. As a result, it becomes essential for investigators to devote their energies to the noteworthy nanoparticles (NPs) in agriculture investigations that have been distributed. It offered a fresh perspective on the development and application of nanoparticles as nanofertilizers and nano-pesticides in agriculture and a way to heighten bio-factor execution. Furthermore, we discuss the relations of NPs with plants, the perils and putrefaction of nanomaterials in plants, and the utility of NPs in the reduction of stress triggered by heavy metal toxicity and abiotic factors. It is imperative that nano-fertilizers are practiced to reduce the environmental maltreatment caused by conventional, inorganic fertilizers. Nano-fertilizers are more sensitive and have the ability to penetrate the epidermis, empowering them to promote nutrient consumption efficiency while reducing nutrient overabundance. A study found that NPs may cause oxidative stress symptoms in higher plants if they adhere to cell surfaces or organelles. Understanding the benefits and drawbacks of using nano-fertilizers instead of conventional fertilizers is valuable, and it is the purpose of this book chapter to provide this information.

Keywords: nanotechnology, nanoparticles, nano fertilizers, abiotic stress, toxicity, green NPs.

INTRODUCTION

Nanotechnology is a multidisciplinary division of science, growing quickly with numerous scientific and technological applications In this field, fundamental ideas from chemistry, engineering, physics, and biology are integrated to develop novel methods for controlling and producing nanoparticles (NPs) NPs within this group are between 1 nm and 100 nm in size on at least one axis . The production, investigation, and application of different NPs are the primary objectives of nanotechnology. Noble metals that include gold, silver, or platinum are used in the majority of the physical and chemical operations used to generate NPs, but these processes are not ecologically benign (Hatami et al., 2016). In order to produce NPs that are safe for humans and the environment, a method must be devised that is able to produce them safely. In order to achieve safety by design, numerous green synthesis methodologies for NPs have been developed. They are secure, straightforward, reasonably priced, reproducible, and scalable. Green synthesis techniques use yeast, fungi, bacteria, and plant extracts to synthesize nanoparticles, thus using various biological systems (Dey and Somaiah, 2022). Green manufacturing of NPs grounded on plants has arisen as the gold standard among these green biological tactics because of its adaptability and relative ease. The biochemical, physical, and biological properties of NPs became more favorable due to their higher surface area-to-volume ratio. By providing specific nutrients to plants in nanoparticle form, nano-fertilizers boost crop yields (Dimkpa and Bindraban, 2016). Three different forms of nano fertilizers are available, depending on the plants' nutritional needs: nanoparticulate fertilizers, micro-nano fertilizers, and macro-nano fertilizers. It is possible to spread nano-fertilizers as liquids or powders if their diameter does not exceed 100 nanometers (Chhipa and Joshi, 2016). In turn, this increases plant uptake and yield by formulating nutrients obtainable to plants. The leading characteristics of nano-fertilizers are briefly outlined as follows: 1) by applying foliar and soil usages that provide the accurate nutrients to augment plant growth; 2) by producing plant nutrients cheaply and sustainably; 3) by having a high fertilization rate; and 4) by acting as a primary protagonist in preventing pollution (Adelere and Lateef, 2016).Nano-fertilizers are also a cutting-edge fertilizer that aids in cleaning up polluted water. The creation of nanoparticles, their value as nano-fertilizers, how they impact soil and plant quality, and their interactions with different plant tissues will all be covered in this chapter's overview. We know of no other book chapter that discusses all of these concepts simultaneously.

NUTRITIONAL DEFICIENCY: ORIGINS AND IMPACTS

Common soil nutrient deficiencies have a detrimental impact on crop productivity, soil health, and farmer revenue. Large volumes of fertilizer are needed to improve crop growth, but because most macronutrients are difficult for plants to absorb, they typically only utilize around half of the fertilizer applied to them. Most macronutrients are also inaccessible to plants because they are insoluble in soil (Zulfiqar et al., 2019). The remaining fertilizer's leaching and discharge all worsen soil, air, and water pollution.Consequently, employing chemical fertilizers to increase productivity damages the agroecosystem over the long term even though it may benefit the economy in the near term. The misuse of chemical fertilizers results in harm to soil health and microflora, disruption of underground food webs, DNA mutations in plants and animals, and changes in ecosystem ecology (Saini et al., 2021; Verma et al., 2022). Several factors, such as temperature, moisture, soil fertility, soil erosion, leaching of nutrients, the excessive use of pesticides and herbicides, and runoff from the surface, have an impact on the plant's overall nutritional status (Kabata-Pendias, 2010; Nongbet et al., 2022). The excessive application of macronutrients like nitrogen, phosphorous, and potassium, as well as a variety of micronutrients, is stunting plant growth and development all over the world (Kabata-Pendias, 2010). In order to improve the operational worth of crops and the animals that cohabit with them, it's essential to develop sustainable alternatives to chemical fertilizers that build on fundamental research and apply ingenuity. This will help us to use nutrients more effectively, add worth, and sweep up the environment. Food security and productivity are two agricultural fields that can both profit from the methodical deployment of nanotechnology. In preventing sickness in plants, both macronutrients and micronutrients are crucial. Using NPs to enhance plant diets may result in improved yields, resilience to stress, and defense against disease attack (Naderi and Danesh-Shahraki, 2013). Study shows that insufficient nutrient levels in agricultural soils call for targeted, site-specific nanotechnological interventions that release the nutrient carrier material in a controlled manner.

COMPARISON BETWEEN TRADITIONAL CHEMICAL FERTILIZERS AND NANO-FERTILIZERS

In less developed nations, chemical fertilizers are frequently sprayed or administered to plants without consideration for the nutritional quality of the soil or the plant. Due to the non-targeted nature of typical fertilizer applications, less fertilizer is used by the plant (use efficiency) than is lost through leaching and seepage from agricultural fields into water bodies and the soil below, leading to consequences for the economy and environment (Nongbet et al., 2022). Overfertilization causes an excess of nutrients, which lowers N fixation, increases the number of diseases and pests that harm soil plants and organisms, and disturbs mineral homeostasis. This contributes to soil deterioration (Kabata-Pendias, 2010).

When urea, the primary N fertilizer, is applied, over 75% of it vanishes due to evaporation and washing away (Rajput et al., 2021). An ineffective fertilizer supply is associated with polluted groundwater and water body nitrate overload, which lengthens lifeless zones in water bodies and releases nitrous oxide into the environment. The third most prevalent chemical that destroys the ozone layer is nitrous oxide. It is a greenhouse gas with a greater potential for global warming than carbon dioxide and methane. Chemically produced N fertilizer has considerably increased anthropogenic interference with the N cycle, which is essential for synthesizing proteins in all species. The gradual, on-demand delivery of nutrients made possible by nanoparticle fertilizers reduces waste (Kumar and Sharma, 2020). Research into nanoscale materials that can carry fertilizers or serve as vectors for innovative nano fertilizers with precise release kinetics can be done using nanotechnology (Zulfiqar et al., 2019). Through the creation and use of metal NPs in nano fertilizers, a sustainable alternative to the current, pricy, and unsustainable conventional chemical fertilization procedures, a "Nano-Bio Revolution" has been launched in the field of nano-enabled NP synthesis technologies. The employing of biological systems to produce these NPs is another benefit of nano-biofertilizers because of the fertilizer's targeted needs-based release and reduced waste (Figure 1) (Davari et al., 2017). NPs are mobile, tiny, easily soluble, and have a huge surface area. They also have a high surface tension, which helps control the discharge of fertilizer. Rapid translocation by NPs boosts security provided by nano pesticides, nano fertilizers, and nano herbicides while also accelerating the release of nutrients from nano fertilizers (Karthika et al., 2018).

BIOSYNTHESIS OF GREEN NANOPARTICLES FROM PLANTS

In the past decade, "Green Chemistry" has received a lot of attention as a key component of "Sustainable Development" (Kates et al., 2012). Growth and development that meets present demands without compromising those of future generations is known as sustainable development (Kates et al., 2012). Because sustainable development places such a strong emphasis on reducing the negative consequences of pollution and making the greatest use of limited natural resources, many chemical businesses rely on it (Omer, 2008). The selection of a green or ecological solvent (the most

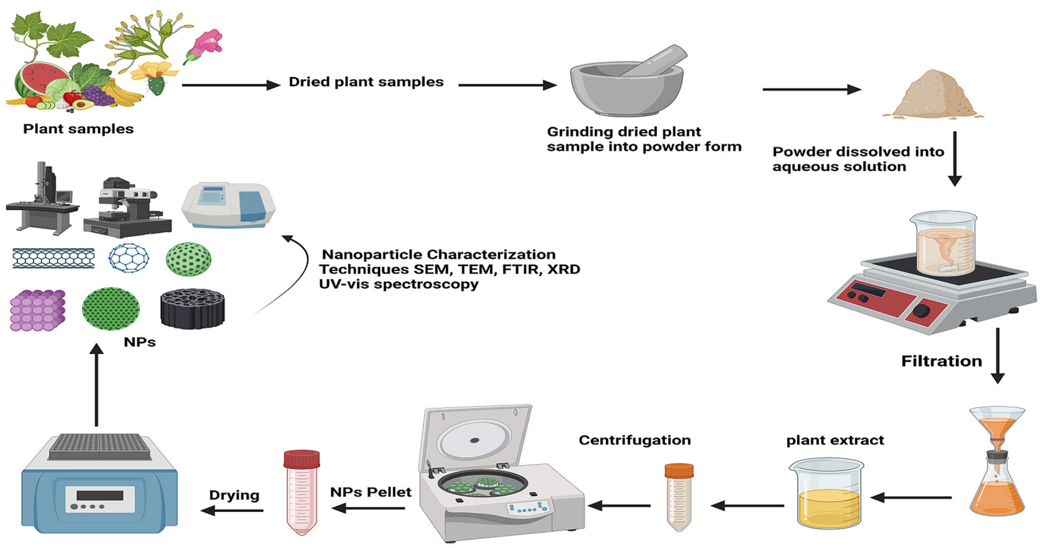

Figure 1. The process involved in the biosynthesis of plant-based green NPs

popular ones being water, ethanol, and their mixtures), a suitable nonhazardous reducing agent, and a safe chemical for stabilization are the three essential requirements for the environmentally friendly manufacturing of NPs (Rakgotho et al., 2022).

Numerous synthetic methods have been used to create nanoparticles, with biosynthetic, chemical, and physical methods being the most common. Chemical processes frequently employ toxic and dangerous substances, which raises prices and presents additional environmental dangers (Narayanan and Sakthivel, 2011). However, green synthesis offers a safe, biocompatible, and environmentally friendly method of producing NPs for use outside of medicine (Narayanan and Sakthivel, 2011). In order to achieve green synthesis, fungi, algae, bacteria, and plants are used. But a variety of NPs have been created utilizing plant materials such as fruits, stems, seeds, leaves, and fruits (Figure 1) (Razavi et al., 2015). The production of NPs with adjustable size, shape, and content is possible using plant extracts. Numerous phytochemicals are present in their extract, some of which may function as organic stabilizing and/or reducing agents in the NPs manufacturing process (Patil and Chandrasekaran, 2020). NPs derived from plants are widely acknowledged to be safer for human consumption than their chemically synthesized parallels, furthermore due to their excessive biological curiosity and an array of conceivable uses in industries like nanomedicine, cosmetics, agriculture, bioengineering, and food science. These NPs need to be fully and precisely described in order to ensure uniformity in their manufacturing, safety, and biological function. To precisely define the synthesized NPs, a wide range of physicochemical approaches are used (Faisal et al., 2021). SEM (scanning electron microscopy), TEM (transmission electron microscopy), PL (photoluminescence analysis), ATR (attenuated total reflection), UV-visible diffuse reflectance spectroscopy (UV-DRS), FTIR (Fourier transform infrared spectroscopy), and DLS (dynamic light scattering) are a few of these techniques (Stefanos Mourdikoudis et al., 2018) (Figure 1).

Fruit and vegetable waste extracts

The majority of food waste in supermarkets is comprised of fresh fruits and vegetables (Eriksson et al., 2012). These might range from remaining fruit pulp from fruit squeezing to the ends of cabbage (Wijngaard et al., 2009). Fruit and vegetable losses by Americans in 2008 totaled $42.8 billion at the retail and consumer level, or around $141.50 per person (Sagar et al., 2018). These can be produced along the entire food supply chain, from farm to table. This includes both pre- and post-consumer operations such as harvesting, transporting, storing, marketing, and manufacturing (Wijngaard et al., 2009). Thanks to the plentiful polyphenols, dietary fibers, enzymes, and proteins present in fruits and vegetables, it is possible to synthesize silver nanoparticles in a way that is both environmentally friendly and sustainable (Wijngaard et al., 2009). Industrial food waste includes fruit pieces including orange peels, banana skins, apple cores, and pear cores. Some of the most popular fruits grown around the world include oranges, grapefruits, lemons, limes, and mandarins (Shen et al., 2013). About 30% (w/w) of the grapes required for creating wine are likely to be abandoned as solid by-products like marcs, pomace, and stems (Shen et al., 2013).

Fruit and vegetable peel extracts

Peels from fruits and vegetables, the most typical processed food byproduct, have been proven to be a rich source of several bioactive substances. Considering their potential application in the environmentally friendly green synthesis of Ag-NPs, fruit peels are frequently wasted during processing (20–30% for bananas and 30–50% for mangoes) (Kowalska et al., 2017). Food waste can also include the peels from apples, white grapes, and red beets (Choi et al., 2015). Comparatively, 115 million tons of citrus fruit are produced annually, of which 30 million tons are used to make juice. After citrus oranges are processed industrially, peel makes up more than half of the wet fruit mass (Choi et al., 2015). Oranges are the most popular citrus fruit with 50 million tons, and its peel accounts for 44% of all rubbish (Rafiq et al., 2018). Investigations on fruit and vegetable waste extracts have been conducted.

Waste cereal extracts

Both during and following the harvesting of the grain, cereal waste is produced. The most frequent harvest-related wastes are straw, stover, peelings, cobs, stalks, bagasse, and other lignocellulosic leftovers. The primary agricultural sector of the world produces somewhere in the neighborhood of 200 billion tons of lignocellulosic biomass annually (Guo et al., 2010). By-products of grain processing include soluble, dried distillers' grains, and gluten meal. According to estimates, the US produced 44 million tons of DDGS in 2018 (Chatzifragkou et al., 2015). Furthermore, China produces about 840,000 tons of genetically modified maize each year, the majority of which is used for feed or is discarded (Zhuang et al., 2013). Grain wastes became more significant as reducing agents for the production of silver nanoparticles as a consequence of their high output. Extracts that function as reducing agents could be created using the leftovers from wheat, corn, and rice cereals. While protein makes up the majority of GM and DDGS, cellulose, hemicellulose, and lignin make up straw and husk waste (Farooq et al., 2012; Li et al., 2019). Extracts of bran, husk, and straw have been used as reducing agents in a number of studies.

THE APPLICATION OF GREEN NANOPARTICLES IN AGRICULTURAL SECTORS

Silver NPs

Silver nanoparticles have found extensive use in a range of areas, including health, industry, and sports, because to their antibacterial qualities (Song and Kim, 2009). In addition to great electrical conductivity, antibacterial qualities, and catalytic skill sets, they have a variety of optical, electrical, and thermal characteristics (Ahmed et al., 2016). Because of their chemical stability, excellent conductivity, catalytic properties, and—most importantly—their antibacterial, antiviral, antifungal, and anti-inflammatory properties (Ahmed et al., 2016). They have been used in electrical components, cryogenic superconducting materials, cosmetics, and the food industry. Plants exposed to silver nanoparticles show increased resistance to fungal, bacterial, and nematode infections as a result of a direct connection between the Ag ions in the silver nanoparticles and the plant's morphology and physiology (Ahmed et al., 2016). According to a related notion, Ag nanoparticles may also speed up the germination of seeds (Kale et al., 2021).

Copper NPs

Copper (I) oxide and copper (II) oxide (Cu_2O) are the two different forms of copper oxide nanoparticles. The CuO form has been the subject of extensive research due to its beneficial characteristics, including as high-temperature superconductivity, spin dynamics, and electron correlation. These materials are used in the process of conversion of solar energy, batteries, high-temperature superconductors, gas sensing equipment, catalysis, and field emission (Ren et al., 2009). Due to their high surface-to-volume ratio, perpetually regenerating surface, and changeable microelectrode potential values, nanoparticles are frequently used as catalysts. Since they are effective against bacteria like *Bacillus subtilis*, they are frequently utilized in the healthcare and wastewater treatment industries (Ruparelia et al., 2008).

Zinc NPs

The most inventive sector of the twenty-first century is nanotechnology. Numerous studies are being conducted worldwide on this aspect of commercializing nano products. Due to their unique properties, nanoparticles have grown in importance when compared to their bulk counterparts. Zinc oxide-based nanoparticles are widely used in various industries, including gas sensing, biosensing, cosmetics, drug delivery, and more. Zinc oxide nanoparticles (ZnO NPs) have exceptional optical, physical, and antimicrobial properties, suggesting they may be extensively used in agriculture. ZnO NPs can be produced chemically using a variety of techniques, including as hydrothermal synthesis, vapour transfer, and precipitation. In addition, ZnO NPs can be biosynthesized using a variety of plant extracts. This green synthesis is more secure and environmentally conscious than chemical synthesis. Due to its extensive application in industry, zincite has gained popularity. Solar cells, gas sensors, chemical absorbents, varistors, hydrogenation catalysts, and photocatalytic degradation catalysts have all been made using ZnO nanoparticles. Additionally, they have been utilized in electrical and optical systems (Pérez-Hernández et al., 2012).

Iron oxide NPs

In environment, iron can be achieved in three different oxides: magnetite (Fe_3O_4), maghemite (Fe_2O_3), and hematite (Fe_2O_3) (Kaningini et al., 2022). Because of their benign toxicity, superparamagnetic properties, and simplicity of separation, magnetic iron oxide nanoparticles like magnetite and maghemite have received a lot of attention (Kaningini et al., 2022). There is a great deal of potential in improving magnetic resonance imaging diagnostics, thermal treatment, and the delivery of drugs by using them (Ali et al., 2016). High-magnetism iron oxide nanoparticles are used in a variety of products, such as magnetic seals and inks, magnetic recording surfaces, catalysts, ferrofluids, MRI contrast agents, and cancer treatment agents, to name a few (Teja and Koh, 2009). Iron oxide nanoparticle use in agriculture is an exciting and attractive technique that still has room for development. For instance, Fe_2O_3 nanoparticles promoted the growth of peanuts by boosting the accessibility of Fe in the soil and plant cells, and by changing the amounts of phytohormones and the function of antioxidant enzyme (Ali et al., 2016). Application via foliage and soil drenching are the two most used ways to give plants iron oxide nanoparticles (Teja and Koh, 2009). Iron oxide nanoparticles can be created using a variety of chemical, physical, and biological procedures (Maswada et al., 2018). It has been established that the manufacturing of iron oxide nanoparticles using biosynthesis is more affordable and environmentally friendly than using physical or chemical means. Since they are made from plant-based components like sugars, antioxidants, amino acids, and proteins, these nanoparticles are harmless to consume (Fathi et al., 2017).

Silicon NPs

By reducing their negative effects, some metal and non-metal NPs, particularly Si NPs, have been found to increase plants' resistance to biotic and abiotic stress (Pinedo-Guerrero et al., 2020). Additionally, it increases plants' resistance to a variety of harmful metals (Alsamadany et al., 2022). Increasing agricultural yields without compromising the environment or human health through nanotechnology, is an economical and non-hazardous process. The use of Si NPs in agriculture is supported by the notion that it will reduce hazardous environmental inputs and high fertilizer prices because they are produced according to greener standards and would mitigate the harmful effects of chemical fungicides. Due to their decision-making qualities, such as their enormous surface area and small size, which allow a realistic distribution in plant tissues, Si NPs can be employed in agriculture (Alsamadany et al., 2022). NPs have been studied by academics and professionals for usage as soil stabilizers. Si NP must first be polymerized in the root tissues before it can be deposited in the shoot (Alam et al., 2022). But more research needs to be done on the confirmed mechanism (Coutris et al., 2012). A variety of pesticides, herbicides, and fertilizers containing Si nanoparticles were applied topically to the plants (Martin-Ortigosa et al., 2014). Si NPs have been proposed as carriers for proteins, nucleotides, and other compounds in flora, in addition to their possible application in agriculture to increase soil water retention (Martin-Ortigosa et al., 2014). The many attractive properties of Si NPs, such as their low production cost, hydrophobicity, high surface area/pore volume, and biocompatibility, contribute to their flexibility. Due to their remarkable adsorption capacity and non-hazardous makeup, silica nanoparticles (Si NPs), for example, have been used to resolve issues in agriculture. Si NPs have recently been utilized to boost plant growth, boost crop yields, and boost disease resistance. Si NPs are continually being investigated and researched for new applications. The second-most significant application of nanotechnology is thought to be the improvement of agricultural output.

TECHNIQUES FOR APPLICATION OF NANO-FERTILIZERS IN AGRICULTURE SECTOR

Uptake of nanoparticles from soil via the root system

NPs pass through the endodermis, the epidermis of the root, and eventually arrive to the xylem, where they are transported to the leaves of the plant. Between 3 and 8 nm, NPs can pass through the cell wall pores and penetrate the cell (Lin and Xing, 2008). Because the casparian strip has wounds, NPs can also enter through the root tip meristem or at the places where lateral roots sprout. To get to the root epidermis, NPs must be able to pass through cell walls and membranes. They subsequently pass via the xylem of the blood arteries. Sizes of cell wall pores range from 3 to 8 nm (Lin and Xing, 2008), although it has been shown that NPs stimulate the creation of huge gaps in cell walls, allowing for their internalization, this makes it challenging for NPs to enter. As opposed to their inability to absorb 18 nm Au NP (Markus et al., 2016), Au NP of size 3.5 nm can be captured by tomato roots. Via its roots, *Arabidopsis thaliana* can take in 14–200 nm spherical silica NPs (Kiefer et al., 2015). Additionally, *Solanum lycopersicum* roots carried 40 nm spherical Au NPs to the shoots (Ahmed et al., 2023). The microelements enter the plant through the feeder root hairs. Organic acids and phenols in root exudates dissolve in microspheres that are enclosed in Ca, Mg, Fe, S, or Zn (Wang et al., 2020). Following the application of fertilizers to the soil, leaching occurs, resulting in the disappearance of nutrients and water and soil pollution. Furthermore, the usage of some agrochemicals is blamed for greenhouse gases and climate change. utilizing mesoporous silica nanoparticles to release specific chemicals into protoplasts under control. Urea coated with polyolefin, neem, and sulfur were some of the treatments used to lessen nitrogen loss in the soil (Younis et al., 2020). In a study, two-layered hydroxide nanocomposites were employed to dispel nutrients gradually. The relationship between soil water retention and integrated superabsorbent fertilizer discharge (Dennis et al., 2015). When it came to gradual release and preserving soil moisture, the surface cross-linked product performed admirably. It's noteworthy to note that plants have NP-responsiveness as well. The size of the holes in the root cell walls of *Z. mays* seedlings decreased from 6.6 nm to 3.0 nm after applying bentonite and TiO_2 nanoparticles (Janmohammadi et al., 2016)

Uptake of nanoparticles from foliar via the stomatal system

The physiological traits of plants affect how well they respond to nanoparticles (Alabdallah and Alzahrani, 2020). NPs usually get absorbed by trichomes, stomata, stigmas, and hydathodes prior to being transported throughout the plant by phloem and xylem (Zhao et al., 2020). The apoplastic and symplastic pathways are the two pathways for NP translocation. NPs, water, and other large molecules are transported through the apoplast, or cell wall, and into the cytoplasm via the apoplastic pathway. However, these macromolecules are unable to migrate freely during this transport due to the size exclusion limits (SELs) of cell walls (5–20 nm) (Mejias et al., 2021). On the other hand, the symplastic pathway entails the passage of macromolecules via plasmodesmata via the plasma membrane. The mechanism of endocytosis enables NPs to enter cells through the cell wall (Schwab et al., 2016). The diameter of the stomata, which ranges from 5 to 20 nm, determines the nanoparticles' capacity to penetrate the plant cell wall and be transferred to the tissues (Schwab et al., 2016). The plasmodesmata's SELs, which have a size range of 3 to 50 nm (Schwab et al., 2016), regulate the material flow along the symplast pathway. The casparian strip hinders transport into the circulatory system (Schwab et al., 2016). SEL of the cell wall, plasmodesmata, and the casparian strip may be affected by enzymes, according to some studies, enabling NPs as large as 50 nm to be internalized, even though SEL is required for the entry and translocation of NPs. Cucumber leaves were discovered to be capable of absorbing and moving CeO_2 NPs throughout the plant (Sangeetha et al., 2021). Spraying Ag NPs on lettuce leaves enables them to be absorbed and dispersed all throughout the plant (Das et al., 2018). In order to increase potato yields, foliar applications of NPK NFs were more successful than edaphic applications of NPK conventional fertilizers (Drostkar et al., 2016). It has been demonstrated that the use of NPK NFs benefits the ecology, economics, and environment. NFs can be used with nanoparticles to more effectively fight phytopathogens. Polymer wall nano capsules can be released from their chemical bonds by enzymes produced by stressed plant cells. When the plant detects an invasion of pathogens, mucilage is secreted (Ha et al., 2019). Additionally, the buildup of nanoparticles on leaf surfaces may cause foliar heating, which may alter gas exchange due to stomatal blockage (Ha et al., 2019).

INTERACTION BETWEEN PLANTS AND NANOPARTICLES

The agriculture sector benefits from scientific and technical advancements because they give us fresh ideas and instruments to tackle enduring problems. Because of breakthroughs in nanotechnology, new nano-formulations for ecologically friendly farming are continually being created (Fraceto et al., 2016). This information can be used to understand the subsequent effects because the most recent generation of chemicals tends to have a rapid impact on plant physiology upon entering the complex plant-soil system. Furthermore, for the controlled distribution of active compounds, it is essential to comprehend whether these NMs interact favorably or unfavorably with plants. As a result, they might present special chances for developing superior nanoparticle-based products. According to reports, natural NM concentrations are also far lower than those considered harmful. However, there are some gaps that require careful safety assessments to be filled appropriately (Fraceto et al., 2016).

The size of NPs must be considered as a critical aspect when researching absorption because there are numerous barriers within plants that range in size from micrometers to nanometers (Fraceto et al., 2016). The cuticle membrane, for instance, is composed of cells of the foliar epidermis. As the epidermis opens for gaseous exchange, a stoma with two guard cells creates a pore of approximately 3-12 nm in width and 10-30 nm in length (Avellan et al., 2021). These stomatal holes allow NPs to freely travel throughout the plant tissues. The trichrome of the stomata and the cuticle layer of the epidermis exhibit distinctly different penetration characteristics. On the leaf epidermis, the cuticle layer, which has an exclusion size limit in the nm range, is more prevalent (Ali et al., 2021). The ability of NPs in the 4-100 nm dimension range to enter the cuticle by disintegrating the waxy layer has been described. NPs with fluorescent tags larger than 50 nm may accumulate in the epidermis just below the cuticle where there are no stomata (Larue et al., 2014). While particles as large as 1 m could not reach the leaves of the *Vicia faba* plant, polymeric NPs with a diameter of 43 nm can (Larue et al., 2014). NPs have a propensity to settle on the substomatal cavity cell wall when they enter the body through the stomata. The plant *Nicotiana benthamiana* may have absorbed 20nm Fe3O4 NPs, according to TEM examination. It is essential to comprehend the path that NPs take once they enter plants since it indicates potential areas of aggregation. Two of the most important pathways for the upward and downward migration of NPs in plants are the apoplast and the symplast. Transport through intercellular spaces is possible via both the symplastic and apoplastic pathways; the former uses the cytoplasm of nearby cells while the latter makes use of the xylem vessels and cell walls of nearby cells (Roberts and Oparka, 2003). Plasmodesmata function as a cytoplasmic link to permit particle movement and intercellular communication between neighboring cells. They are enclosed in particles that are barely 3 nm in size and range in diameter from 20 to 50 nm (Roberts and Oparka, 2003).

The transport, absorption, and trafficking of NPs within plants give these particles a significant amount of freedom. The NMs' energy and surface charge modify the surface receptors, transporters, and specialized membrane proteins of plants in a physicochemical manner (Perez-Labrada et al., 2019). NPs with different surface charges clearly differ from their unaltered counterparts in terms of their capacity for aggregation and surface characteristics (Hotze et al., 2010). The cell wall, a biological membrane found within the leaves, is composed of an uneven distribution of components with surface potentials of 15 and 45Mv for cellulose fibers and 15 and 45Mv for lignin, respectively (Santiago et al., 2013). The negatively charged cell wall can aid in the absorption of the positively charged NPs into tissues. Ion exchange at the negatively charged surface of plant cell walls may facilitate the penetration of cationic NPs rather than anionic NPs (Meychik et al., 2005). Nevertheless, increased transport efficiency has a significant positive impact on negatively charged NPs. The mobility and uptake of AuNPs are dependent on their surface charge, which is explained by Zhu et al.'s demonstration of significantly higher binding of NPs with a positive charge at the surface of the root. However, it was discovered that negatively charged NPs internalized and translocated at higher rates. (Meychik et al., 2005). Negatively charged CeO NPs demonstrated enhanced shoot internalization but little root accumulation, possibly by conquering electrostatic repulsion. Positively charged CeO NPs powerfully bind onto the surface of roots (which are negatively charged) (Lui et al., 2019; Hu et al, 2020).

TECHNIQUES FOR THE QUANTIFICATION AND EVALUATION OF NANOPARTICLE DISTRIBUTION

There is an urgent need for further information on the quantification of NP uptake and translocation within plants as well as when they are released into the environment, in addition to the need for novel techniques to monitor plant-NM interactions. In this investigation, iron (Fe_3O_4) nanoparticle content and uptake in the roots and leaves of pumpkin (*Cucurbita maxima*) plants were measured using a vibrating sample magnetometer (Zhang et al., 2022). Similar to this, Fe_3O_4 NPs may be found, measured, and tracked in various plant organs thanks to their magnetization dependence on temperature and magnetic field (Govea-Alcaide et al., 2016). The main obstacle to the tracking and translocation of Fe_3O_4 NPs is the difficulty in differentiating between intact Fe_3O_4 NPs and leached ions. Combining magnetic particle spectrometry with conventional atomic absorption solves this issue (Govea-Alcaide et al., 2016). Additionally, electron microscopy was used to observe the translocation of MWCNT and C70 fullerene from the roots to the leaves of rice; however, the number of NPs absorbed by the plants was not measured (Lin et al., 2009). To measure MWCNT uptake in wheat and rapeseed plants, raman spectroscopy and transmission electron microscopy (TEM) were used in this study (Larue et al., 2012). The detection and localization of different NMs in plants can be aided by the use of important imaging methods including X-rays and computed tomography (CT). Recently, a combination of improved darkfield (DF), X-ray computed nano tomography (nano-CT), and hyperspectral (HIS) imaging was employed to pinpoint the precise location of gold NPs in *A. thaliana* roots. Better tools for characterizing and evaluating the NP-plant interaction at the cellular level can be obtained by combining 2-D (DF-HSI) and 3-D (nano-CT) approaches (Larue et al., 2012). Another non-invasive, highly susceptible method for visualizing NPs in lettuce (*Lactuca sativa*) is to combine autoradiography, positron emission tomography (PET/CT), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) (Zhang et al., 2022). In a pioneering investigation, researchers used time-resolved, laser-induced fluorescence, and UV-visible spectra to assess the impact and interaction of garlic (*Allium sativum*) with TiO_2 NPs. Because of this, the garlic plants' leaves had more chlorophyll and were photosynthesizing more vigorously than the control plants. The red to far-red chlorophyll fluorescence intensity ratio decreased, but researchers also noticed an increase in chlorophyll content and photosynthetic activity (Bharti et al., 2018). In vivo detection of MWCNTs, TiO_2, and Cerium oxide NPs in wheat tissues was accomplished using the ground-breaking technique of two-photon excitation microscopy (Wild and Jones, 2009). Several additional essential techniques, include spectroscopy and microscopy. Microscopy techniques provide a clear advantage for assessing NPs in different materials, but they also have a number of significant disadvantages, including the need for sample preparation, the analysis of just a portion of the sample, and the provision of very limited 3-D imaging. Because of this, single-particle ICP-MS (SP-ICP-MS) analysis using ICP-MS (Inductively-coupled plasma mass spectrometry) is a potential method for identifying, describing, and counting NMs (Wild and Jones, 2009). SP-ICP-MS is also used to measure the uptake of CuO NPs in lettuce, collard greens, and kale for human consumption (Keller et al., 2018). Since NMs easily undergo chemical changes as soon as they enter the plant, analytical techniques based on mass spectrometry aid in differentiating between their various forms. To determine what happened to the ZnO NPs contained in the lettuce, one method used SP-ICP-MS and ESI tandem MS (Keller et al., 2018). We quantified the Au NPs in watermelon plants using ICP-MS to analyze the pathway of uptake and accumulation (Raliya et al., 2016). Where these techniques' combined benefits really stand out is when they are used in tandem. Nath et al., utilized SEM, EDS, and SP-ICP-MS to investigate the concurrent absorption, retention, and dispersion of Cu, Ag, and ZnO NPs in *A. thaliana* (Keller et al., 2018). Similar to this, the absorption and size dispersion of TiO_2 NPs in rice plant tissues are reported using the combination of three orthogonal techniques: SP-ICP-MS, electron microscopy, and ICP-OES.9.

CONSTRUCTION OF FERTILIZERS AT NANO-SCALE

Due to the growing need and desire for environmentally safe, effective, and non-toxic nanoparticle formation approaches, bio-fabrication of NPs using biological processes has attracted a lot of interest. NPs are produced by substances such as alkaloids, pigments, amines, enzymes, proteins, and phenolic compounds in plants and microorganisms (Abdelnour et al., 2020). Physical methods are excessively expensive whereas chemical processes use hazardous chemicals and have negative environmental effects.

APPLICATION OF NANO-FERTILIZERS IN AGRICULTURAL PRODUCTION

The ease with which plants can acquire conventional fertilizers is lowered in a number of ways when such nutrients are applied to the soil. Foliar spray is the best method for managing nitrogen deficits and improving crop production and quality as a result (Ombodi and Saigusa, 2008). Other advantages of less fertilizer use include reduced soil toxicity and improved nutrient utilization. More than 10 nm-sized nano-coated substances have been shown to promote stomata penetration. (Tarafdar et al., 2014). Nano-fertilizers are an efficient delivery method due to their huge surface area, controlled release kinetics to the desired area, and high sorption propensity (Tarafdar et al., 2014). In many instances, nano-carriers are able to properly time and place the delivery of nutrients. It is necessary to present the most up-to-date studies on the impact of nano-fertilizers on crop yield, efficiency, resilience to abiotic stress, and reduction in heavy metal toxicity.

Plant growth and development

The accessibility of nutrients is increased by nano-fertilizers, which is essential for the biochemical and physiological processes involved in crop growth. Due to how easily nano NPK was absorbed by the leaves through the exchange pores or stomata, its use promoted the growth of wheat leaves. Cotton and pearl millet both experienced the same impacts (Tarafdar et al., 2014). The foliar application of Zn nano-fertilizer dramatically accelerated plant growth and dry biomass production (Gharaei et al., 2015). It's possible that physiological systems like antioxidant activity and chlorophyll content will also benefit as plant quality and production increase (Rezaei and Abbasi, n.d.). Zinc activates crucial enzymes involved in the metabolism of glucose and protein, growth regulation, biological membrane integrity, and pollen production in addition to having an impact on natural auxin (IAA) synthesis (Sharifi et al., 2016). The levels of hormones that promote plant growth increased in response to the application of nano Zn fertilizer. The pattern of foliar nano-Fe fertilizer administrations to both fodder corn and *Ocimum basilicum* L. was consistent (Sharifi et al., 2016). By promoting N assimilation, enhancing photo-reduction activities of photosystem II and the electron transport chain, and removing reactive oxygen species, TiO_2 foliar sprays also increased plant total dry matter.

NPs-based advancement of plant physiology

Both physiological and biochemical measurements showed a noticeable improvement after crops were fertilized with nanoparticles. The overall chlorophyll content of sunflower leaves was raised by biocompatible magnetic nano-fluid (MNF), however at high concentrations (>0.75% MNF), the chlorophyll content dropped (Pîrvulescu et al., 2015). The carotenoid, anthocyanin, and chlorophyll contents of maize crops were significantly increased by foliar application of $nTiO_2$, resulting in a larger overall harvest (Morteza et al., 2013). After misting microscopic TiO_2 particles onto leaves, it was discovered that the amounts of anthocyanin and chlorophyll in barley were increased (Gupta et al., 2022). In actuality, n TiO_2 strengthens the structure of the chlorophyll, enhances RUBISCO activity, boosts pigment formation, and increases the chlorophyll's capacity to absorb light. Spinach grew more and had higher protein and N metabolism levels after being treated with micro TiO_2 (Cai et al., 2019). The photosynthetic rate of spinach treated with $nTiO_2$ was found to be 29% higher and the leaf chlorophyll content to be 17 times more than that of spinach treated with the control treatment (Gao et al., 2013).

In cotton and soybean crops, nano Zn fertilizer increases polyphenol content while decreasing peroxidase, catalase, and oxidase activities (Sheykhbaglou et al., 2010). A pearl millet crop treated with foliar Zn nano-fertilizer showed improvements in plant dry biomass, chlorophyll, and total soluble leaf protein (Tarafdar et al., 2014). After being treated with nano-Zn, the amounts of essential oils, phosphate, and chlorophyll in savory plants all increased (Gharaei et al., 2015). The ability of the rice crop to produce antioxidants was enhanced by using nano-fertilizers. Plants create antioxidant secondary metabolites to protect them from environmental stresses such salt stress, water stress, and nutritional insufficiency. Since the nano fertilizer is more easily absorbed by plant cells, it offers enough nutrients to boost antioxidant activity.

The effect of nano-fertilizers on crop yield

Researchers have recently looked into whether nano-fertilizers could increase agricultural output. The success of harvesting wheat was greatly increased by using foliar sprays of nano-fertilizer (Drostkar et al., 2016). Chickpea yield and production components increased as a result of increased growth hormone synthesis and metabolic improvements following foliar application of NPK nano fertilizers (Drostkar et al., 2016). Nano-fertilizer use has a major impact on cotton productivity. The application of nano-fertilizers can improve the development of chickpeas (Drostkar et al., 2016). Pearl millet's grain yield increased by 37.7% after being sprayed with Zn nano-fertilizer on the leaves of the plant (Drostkar et al., 2016). Additionally, when sunflower plants were treated with nano-Zn, the amount of oil in the seeds rose (Rajput et al., 2018). Higher zinc bioavailability in groundnut crops due to nano-Zn oxide resulted in increased pod yield (Prasad, 2008). Nano Zn's high surface area-to-volume ratio enhances Zn productivity and absorption (Pérez-Hernández et al., 2012). Nano-Zn fertilizer only needs to be administered once every ten years, as opposed to every five years for traditional $ZnSO_4$ fertilizer (Thounaojam et al., 2021). After soil was amended with nano-Zn oxide particles at a 40 ppm concentration, rice grain production and its contents both increased (Ghasemi et al., 2017). ZnO, MgO, and CuO metal oxide nanoparticles were applied topically to improve the production of seed cotton by 33, 22 and 18%, respectively. Using foliar sprays of nano-zinc (Zn) and boron (B) fertilizers increased pomegranate fruit output (636 mg Zn tree-1 and 34 mg B tree-1) (Davarpanah et al., 2016). Farmers can impact the growth of the crop and increase both production and production elements by spraying $nTiO_2$ on the crop's leaves (Janmohammadi et al., 2016). It has been demonstrated that the increase in photosynthetic activity brought on by $nTiO_2$ spraying enhances yield characteristics and the quantity of photo assimilates found in leaves (i.e., source capacity). The application of $nTiO_2$ also markedly improved fertilizer use efficiency and crop productivity (Janmohammadi et al., 2016). Increased photosynthetic and nitrogen metabolism caused by $nTiO_2$ led to more fresh and dried plant mass (Janmohammadi et al., 2016). Additionally, the nanoparticle $nTiO_2$ photocatalyst activity promoted pigment production, enhanced chemical processes, and converted light energy into active electrons in maize, aiding in the development of the plant and enhancing grain output (Zahedi et al., 2021). Fe nano-fertilizer use increased the yield of the soybean crop (Sheykhbet al. 2010). In comparison to bulk Fe, spraying black pea plants with 0.5 g L-1 nano-Fe led to larger increases in pods per plant, 1000-seed weight, yield, and chlorophyll content (Delfani et al., 2014). According to another study, spraying nano-Fe (2%) on leaves increased grain yield by 23.3% when compared to the control (Jaberzadeh et al., 2013). Manganese (Mn) nanoparticles were used to increase the yield and yield components in *Vigna radiata* (L). (Ghafariyan et al., 2013). Production and quality of peanuts increased due to the usage of nano-Mn, nano-Fe, and nano-Zn (30ppm), which increased nutrient utilization efficiency (Mekdad, 2017). The antibacterial properties of nano-silver led to an increase in potato tuber yields when applied foliarly, which suggests that healthier seed tubers may stay in the soil for longer and produce stronger plants (Davod et al., 2011). To boost plant height, lateral branching, seed weight per plant, pod maturity, pod production, seed length, seed quantity per plant, pod and seed yield, and all biological processes, peanut plants received foliar applications of nano-chelated molybdenum (Davod et al., 2011).

Nutrient supplementation is required for improved crop quality. When nano-fertilizers were applied in place of traditional fertilizers, crop quality increased. Metal oxide nanoparticle use improved the consistency and durability of cotton fiber (T. N. V. K. V. Prasad et al., 2012). Peanuts cultivated using nano-fertilizer had higher protein content (T. N. V. K. V Prasad et al., 2012). More crude protein and soluble carbohydrates were produced on fodder maize when foliar nano-Fe and Zn fertilizers were used as opposed to bulk materials (Sharifi et al., 2016). Zinc is necessary for the creation of starch, carbonic anhydrase, chlorophyll, and other compounds that are produced during photosynthesis. As a result, Zn fertilizers boosted levels of soluble carbohydrates, accelerating the development of carbohydrates (Sharifi et al., 2016). After being treated with nano-fertilizers, peanut seeds' total protein, oil, soluble sugars, and starch contents increased (Zulfiqar and Ashraf, 2021). Plants need zinc to produce proteins (Pérez-Hernández et al., 2012). Zn promotes the growth of roots and helps the intake of essential nutrients, such as nitrogen (N), which is necessary for the synthesis of protein. In particular, zinc enhances the metabolism of indole acetic acid (IAA), proteins, and carbohydrates, which promotes the synthesis of starch and seed maturity (Yu et al., 2020). Black-eyed pea seed protein content was more impacted by nano-Fe than bulk Fe (Jiang et al., 2021).

THE ROLE OF NANO-FERTILIZERS FOR THE MANAGEMENT OF CLIMATE CHANGE TO MITIGATE THE EFFECT OF ABIOTIC STRESSES

Green synthesized NPs are widely documented to play a vital part in resetting plant growth and development in addition to being involved in the regulation of abiotic stress management.

Salinity stress

Plants' main metabolic processes are impacted by the osmotic and ionic stressors brought on by salt (Van Zelm et al., 2020). An overabundance of sodium and chloride ions restricts plant growth and development because they interfere with ionic balance, cellular metabolism, and membrane function (Flowers and Colmer, 2015). Stressed plants have salinity tolerance responses that help to counteract these antagonistic reactions. These responses are crucially triggered by the maintenance of ionic homeostasis and osmotic potential. Numerous studies have demonstrated that green artificial nanoparticles (green NPs) can reduce the negative effects of salt stress on plants. Plants subjected to Se NPs (100 ppm) made from the leaves of *H. vulgare* showed improvements in root and shoot attributes (length, fresh weight, and dry weight), flavonoids, phenolic, and photosynthetic pigment levels, and a decrease in stress markers (MDA and H_2O_2)(Habibi and Aleyasin, 2020).

Additionally, it has been demonstrated that NPs made from plant extracts are helpful for triggering stress-responsive signaling. The detrimental effects of salinity stress on triticale callus were shown to be significantly reduced by calcium oxide NPs (1.5 ppm) produced from *P. granatum* fruit extract (Yazıcılar et al., 2021). Evidence from confocal laser scanning microscopy of calcium ions (Ca^{2+}) accumulation in triticale cultivars suggests that under salt stress conditions, CaO NPs may act as stress signalling transducers for Ca^{2+}-mediated plant stress responses (studies and 2006, 2006). Surprisingly, the NPs are also recognized for regulating nutritional homeostasis and shielding plants from ionic toxicity during salinity stress (Wahid et al., 2022). For instance, foliar application of biosynthesized AuNPs significantly affected shoot and root ionic contents, improved nitrogen (N) metabolic activity, and non-enzymatic antioxidant contents (AsA and GSH), with reduced ROS generation and lipid peroxidation under salinity stress (Wahid et al., 2022). SNPs (50, 100, and 200 M) derived from *O. basilicum* leaves were found to increase the nutritional content of *T. aestivum* under salinity stress. These nutrients included nitrogen (N), phosphorus (P), and potassium (K), with an improved ionic ratio of potassium to sodium (K^+: Na^+), as well as the acquisition of cysteine, free amino acids, and total soluble proteins. The effect of ZnO-NPs (17 mg L^{-1}) synthesized from *Carica papaya* extract on the antioxidant metabolism in *Carthamus tinctorius* under salinity stress was also studied, and it was discovered that ZnO-NPs increased the activity of antioxidant enzymes and the proline content while decreasing the production of ROS (H_2O_2, O_2, superoxide radical, and MDA) (Yasmin et al., 2020).

Drought stress

Drought is one of the most important abiotic factors that reduce crop production and quality.A water deficit results when there is an anomaly in the dynamics of temperature, light, and rainfall (Das et al., 2019; Hasanuzzaman et al., 2017; Saxena et al., 2013). Artificially produced drought stress causes several responses in plants, including adjustments to growth features, biochemical adjustments such as adjustments to enzyme antioxidant activity, adjustments to protein and metabolite levels, and more using phytogenic NPs is one possible method for minimizing drought-related plant mortality. Using a *Chaetomorpha antenna*, some bare iron NPs (Fe-NPs) and some coated with citrate compounds were created (Drostkar et al., 2016).

These NPs have been shown to boost the tolerance of *Setaria italica* to drought stress through positive modulation of enzyme antioxidant activities, such as CAT, SOD, POX, and osmolytes concentrations. Fe-NPs improved *S. italic*'s photosynthetic efficiency, growth characteristics, and a wide range of physiological reactions at doses between 50 and 120 mg L-1. In order to lessen the effects of drought stress, Se-NPs (30 mg L^{-1}) produced from *A. sativum* bud extract were administered to *T. aestivum.* These Se-NPs dramatically increased plant height, biomass accumulation, leaf area, number, and length while lowering ionic leakage and lipid peroxidation, which reduced the cellular toxicity brought on by drought stress(Ahmed et al., 2016; Ikram et al., 2020; Naveed Ul Haq et al., 2017).

Heavy metal stress

Rapid globalization seriously pollutes the environment by increasing harmful metal emissions. Once heavy metals are deposited in soil, they negatively affect soil dynamics and the way that microorganisms are organized, which lowers soil fertility and reduces crop productivity (Kacholi and Sahu, 2018). Heavy metal stress has a deleterious impact on water potential, photosynthetic efficiency, and growth characteristics, which can ultimately result in crop failure (Morales-Díaz et al., 2017; Nazir et al., 2020). However, numerous studies have demonstrated that photogenic NPs can control plant physiological processes and development in response to heavy metal stress, leading to the induction of tolerance mechanisms. For instance, the effectiveness of zinc oxide nanoparticles (ZnO-NPs) generated from *Ulva lactuca* (25 mg L^{-1}) on *Leucaena leucocephala* in the presence of heavy metal stress brought on by lead (100 mg L^{-1}) and cadmium (50 mg L^{-1}). These green synthesized ZnO NPs significantly enhanced plant growth and photosynthetic pigments in heavy metal-stressed *L. leucocephala*.(Venkatachalam et al., 2017). Similar enhancements in plant biomass, photosystem II (PSII) quantum efficiency, chlorophyll content, and crop yield were seen after Cd-stressed O. sativa was treated with Fe_3O_4 NPs (0.5 mg g1) produced from husk extract of *Cocos nucifera* (Sebastian et al., 2018). In a different study, Fe_3O_4 NPs (0.5 g) synthesized from *Hevea barsiliensis* bark extract were found to increase biomass, maintain nutritional homeostasis, and lessen stress-induced oxidative damage in O. sativa (Sebastian et al., 2018). It was discovered that increasing the plant height, spike length, chlorophyll content, and grain yield of *Trianthema aestivum* by foliar applying TiO_2 NPs (100 mg L^1) synthesised from leaf extract of *Trianthema portulacastrum* and *Chenopodium quinoa* was advantageous (Ullah et al., 2020). When *Helianthus annus* is treated with SNPs (100 M) made from *O. basilicum* leaf extract, it becomes resistant to the stress reactions brought on by Mn (100 mM) (Saad-Allah and Ragab, 2020). This process also lowers ROS-mediated lipid peroxidation while increasing the amount of crude protein, total amino acids, and cysteine in the plant. After *V. radiata* was treated with TiO_2 NPs (0.1%) made from *Musa paradisiac* leaf extract, the buildup of As^{3+} ions were decreased, protein content rose, and enzyme antioxidant activities (SOD, CAT, and APX) were raised (Venkatachalam et al., 2017). ZnO NPs (25 mg L^1), which are essential for activating the ROS-scavenging system (SOD, CAT, and POX), also prevented Pb from inducing physio-biochemical alterations (Venkatachalam et al., 2017).

Heat stress

One of the most important abiotic stresses linked to climate change in recent years is heat stress, which hurts crop output globally (Sheiha et al., 2020). Heat stress lowers plant output and development (shoot and root) (Abdelnour et al., 2020).Additionally, it contributes to senescence, fruit damage, abscission, and leaf burning. Green synthesised NPs, however, can be used to lessen the damaging effects of heat stress on plants. The literature does not adequately describe the NP-mediated acclimatized responses of plants to high-temperature stress. Researchers discovered that using silver nanoparticles (Ag NPs) made from *Moringa oleifera* leaf extract at concentrations of 50 and 75 mg L1 significantly decreased levels of malondialdehyde and hydrogen peroxide and improved *T. aestivum*'s antioxidant defence system in response to heat stress (Khalid et al., 2022).

Nanotechnology in agriculture: benefits and risks

Nanoparticles are a promising new technology with applications in medicine, agriculture, and other vital fields. Yet, it is still unclear what dangers these compounds represent to people and ecosystems. The research on the potential toxicity of nanoparticles and the development of safe usage methods are referred to as nano-toxicology (Riediker et al., 2004). Various aspects, including biological components, chemical components, shape and size, and the reactions in the media of usage, can make it impossible to compare the protective or toxic character of these nanoparticles (Riedeiker et al., 2004). For each nano-product, toxicological data must be produced to determine whether there are NPs residues in the environment or biological systems (Oberdörster et al., 2005). However, there is currently insufficient proof that NPs directly cause human illness. According to Haji et al., they have been hypothesized to have DNA damage and cell inflammatory responses as their genotoxic impacts, both of which can have toxicological consequences (Oberdörster et al., 2005). Contrarily, the advantages to the environment, financial stability, and biological sustainability brought about by the use of nano goods in crop promotion are more obvious. While nanofertilizers improve plant health, nanomaterials increase the ability of plants to withstand stress brought on by abiotic or biotic causes (Tiwari et al., 2012). The risks of nanotechnology should be assessed before it is used. The possible effects of a novel nano-fertilizer on the environment and human health should be assessed, confirmed, and mitigated through regulatory control and product redesign before it can be released onto the market (He et al., 2015). Particle size, dosage, fabrication materials, etc all play a role in nanoparticles behaving as dangerous elements (He et al., 2015). The findings of research by pullagurala et al. (2018) showed that greater amounts of NPs have detrimental impacts on plants, while lesser dosages applied in specific situations have favorable effects. Higher levels of tailored nano textiles (>500 mg L-1) were found to be phytotoxic, while treatments at lesser amounts (50mg L^{-1}) had a positive impact (Jiang et al., 2021). Higher concentrations of ZnO NPs caused the roots of plants to become clogged, which prevented them from absorbing essential nutrients. (Djanaguiraman et al., 2018). By interacting with other media, NPs generated from chemicals can be poisonous and release dangerous byproducts. The trend in synthesizing nanoparticles using bio-strategies aims to overcome this issue. As NPs are toxic to marine microflora but harmless to microorganisms of soil, the environment has an impact on the safety and behavior of nanoparticles. When asked about the potential risks associated with NPs goods, the US Food and Drug Administration (FDA) concluded that they posed no threat to human health.

The potential of green-synthesized NPs as a unique interface between nanotechnology and agro-environmental sustainability is nevertheless constrained by several restrictions and limitations. Plant material selection, synthesis conditions, product quality, control, and application are among the areas where green synthesis of NPs faces difficulties (Mahakham et al., 2016). For instance, gathering plant extracts can be time-consuming because some plant materials are only prevalent in endemic areas. This has an impact on the number of biocompatible NPs that can be produced globally. Because of the high energy needs, extended reaction periods, and utilization of commercial chemical compounds as oxidizing and/or reducing agents, the task of synthesizing NPs is not simple. The most crucial criteria by which to assess the quality of synthesized NPs are their shape and size. Because genetic heterogeneity within or across plant species, which is exploited in the synthesis of NPs, is not well understood, high-throughput instrumentation is required for the purification and characterization of NPs. Because their conversion rate and yield during synthesis are lower than those of chemically synthesized NPs, the economic advantages of NPs are reduced. To overcome the constraints and challenges provided by many elements during NP synthesis, it is vital and required to look at the incredibly promising outcomes from the green synthesis of NPs. With the aid of cutting-edge scientific concepts, practical challenges in the synthesis of NPs and their applications can be avoided. For instance, decreasing the use of high-energy technologies, optimizing products, and preserving nanoscale items for extended periods are better alternatives than using native or seasonal plants as raw materials.

CONCLUSIONS

Due to the growing demand for green chemistry and nanotechnology, green synthetic methods have been developed to produce nanoparticles using microbes, plants, and other organic sources. A significant area of research has been developing environmentally friendly ways to synthesize NPs. Plant extract-mediated NPs have attracted a lot of interest because of their easy availability, low cost of production, lack of toxicity, and environmentally acceptable composition. Numerous unique plant substances speed up and accelerate the production of compounds. As an intriguing and developing area of nanotechnology, the production of green nanomaterials using trousers has the potential to dramatically improve environmental conditions and progress the field of nanoscience in the long run. The use of these green plant-based nanoparticles (NPs) in different biological domains, including medicine, sensors, biotechnology, cosmetics, agriculture, dye degradation, bioengineering sciences, imaging, optics, catalysis, food packaging, textile engineering, and others, is becoming more and more common. These NPs have potential as a medication delivery system for the biomedical sector in the future. Numerous potential uses for these environmentally friendly

NPs exist, including eradicating phytopathogens in agriculture and purifying contaminated water supplies. There are still concerns regarding the potential effects on people and other animals, as well as the environmental accumulation and influence of these particles, despite the fact that this environmentally friendly and low-impact method of producing NPs is gaining recognition and is projected to expand quickly in the years to come. An important development in the manufacturing of consumer items and the study of materials is the development of designed nanoparticles. Although nanotechnology is still relatively new to agriculture, it has the potential to significantly modify agricultural systems, particularly with regard to problems with fertilizer treatment. Nano-fertilizers have a significant impact on agricultural output since they lower fertilizer prices and raise concerns about emissions. Since they are more soluble, reactive, and cuticle-penetrable than traditional fertilizers, nano-fertilizers have the potential for targeted administration and controlled release. Nano-fertilizers improve crop development, yield, quality, and the efficiency with which nutrients are used while lowering the toxicity of heavy metals and stress brought on by abiotic factors. However, rather than focusing on the benefits and use of the technology itself, the potential drawbacks of excessive consumption and inefficient operation have attracted more attention.

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