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Green Nanotechnology: A Modern Tool for Sustainable Agriculture – a Review

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ABSTRACT

The significance of building sustainable farms has been highlighted in the search for food security. Traditional farming methods in Nigeria have resulted in low agricultural yields. Using modern technologies, such as nanotechnology, is crucial in the current circumstances to address the growing need for food crops. Such objectives have given birth to nanotechnology as a frontier for the twenty-first century. Nanoparticles may be helpful in the treatment and monitoring of diseases affecting crops because they specifically target microorganisms. Crop diseases are fought by nanoparticles, including carbon nanoparticles, silver nanoparticles, and silica nanoparticles. Formulating an edible coating, with encoded nanoparticles, is one such technique for preserving and storing food. Agricultural fields can be equipped with nano-sensors to track soil fertility and other agro-climatic factors. Nanomaterials are utilized to remediate deficient soils and offer a clever, unique, environmentally-responsible, and long-lasting solution. Green nanotechnology may be used for improving the hygiene of food items, leading to a better lifestyle for the general public. An adequate substitute for better recycling of agricultural waste could be nanotechnology. These are ideal raw materials for biochar, renewable energy, and nano-silica. Agriculture also uses barcode technology and nano-based identifying markers. The intentional use of nanomaterials in agricultural endeavors may have unanticipated health effects. Future agricultural issues like food security have great potential to be solved with the help of nanotechnology applications, particularly in developing countries.

Introduction

The importance of establishing sustainable farms has been emphasized in the quest for food security, among many other issues (Igiebor et al., 2019; Ikhajiagbe et al., 2021). Agriculture is one of the most significant and dependable businesses since it offers food and raw materials to companies that need them (Tipu et al., 2021). Agriculture is an activity through which food and pastures are supplied and maintained. It is a generator of revenue in underdeveloped countries. In Nigeria, agriculture suffers from a low level of production as a result of traditional farming practices. Since Nigeria's population is rapidly rising, current situations are happening at a critical time, necessary to employ current technologies such as nanotechnology to meet the ever-increasing need for food crops.

Nanotechnology is a discipline of science concerned with the perception and management of tiny substances, with sizes of 1 – 100 nanometers (Ikhajiagbe et al., 2021). In underdeveloped countries, food shortages are dire. Green nanotechnology can save hundreds of

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millions of lives each year, so this technology should become universally available. We must submit to the fact of growing demands and provide the necessary funding and support (Ikhajiagbe et al., 2021). To maximize output levels, drought and insect-resistant crops with higher mineral uptake are required. According to Alfadul et al. (2017), nanotechnology will raise crop productivity by withstanding environmental conditions, detecting and controlling crop diseases, and improving crops with effective mineral pickup capacities from the soil. Although scientific studies on the applications of nanotechnology in agriculture would be less than a decade old, nanotechnology has the potential to develop this industry substantially.

Fertilizers are used to supplement macro and micronutrients that are lacking in the soil. They have a direct impact on plant development and agricultural yield (Tipu et al., 2021). Chemical fertilizers, on the other hand, are not an economically viable solution to crop productivity and they harm soil health by generating hazardous substances as a result of chemical interactions. Chemical fertilizers and pesticides, as well as other agricultural problems, may be addressed using nanotechnology.

Green nanotechnology could help increase crop yields in a variety of ways (Ikhajiagbe et al., 2021), including (i) developing crops that can withstand extreme temperatures, (ii) creating insecticides targeted for specific insects, (iii) addressing global warming issues, and (iv) developing nanotubes to retain rainwater in the soil such that crops can utilize it during droughts.

History of nanotechnology

New technologies and science are frequently inspired by human desires and ideas. Nanotechnology is a 21st-century frontier that emanated from such aspirations. The study of nanoparticles (NPs) has a lengthy history of observation and inquiry. In 1925, the Nobel Laureate in Chemistry, Richard Zsigmondy, was the pioneer of the theory of a nanometer. According to Bayda et al. (2020), Richard was also the first to evaluate the size of the particles of gold colloids using a microscope, coining the word "nanometer" in the process.

Richard Feynman, the father of modern nanotechnology, was awarded the Nobel Prize in Physics in 1965. In his words, he stated that "There is plenty of room at the bottom." For an atomic-level paradigm that alters matter, he proposed this at a Caltech meeting, hosted by the American Physical Society in 1959. Feynman's assumptions have been proven since then, and his original thinking has opened up new horizons. A Japanese physicist, Norio Taniguchi, coined the word "nanotechnology" to illustrate semiconductor activities on the bid of a nanometer. Nanotechnology, according to Norio, is the process of using a single atom or molecule to process, separate, consolidate, and distort materials. Eric Drexler of the Massachusetts Institute of Technology (MIT) combined Feynman's ideas with his book, "There is Plenty of Room at the Bottom." Taniguchi used the phrase "nanotechnology" in his 1986 book (Bayda et al., 2020). Drexler envisioned a nanoscale sequencer that could make copies of itself and other substances of any complication. Drexler's perspective on nanotechnology is referred to as "Molecular Nanotechnology."

New nanoscience and nanotechnology fields sparked a rush of interest around the turn of the century. The popular impression of Feynman in the United States, as well as his notion of affecting material at the atomic level, influenced the national science agenda. In a speech at Caltech (2000), President Bill Clinton pleaded for the endowment to investigate this ground-breaking technology and approved the 21st Century Nanotechnology Research and Development Act into law, three years later. The Act established the National Technology Initiative (NNI) to make nanotechnology research a national priority (Bayda et al., 2020).

Nanotechnology currently has a daily impact on people's lives. There are numerous and diverse potential advantages. However, since nanoparticles are frequently consumed by humans, there is indeed a great deal of uncertainty about environmental and health issues. Emerging technological disciplines such as nanomedicine and nanotoxicology have resulted in the emergence of these issues. The investigation of potential effects that can harm health by nanoparticles is termed nanotoxicology (Barhoum et al., 2022). Conversely, owing to a deficiency of credible test results, the threat to human health remains a severe concern. The annual symposium on nanotechnology and the environment was held at the American Chemical Society (ACS) meeting in 2003. It was mostly dedicated to green nanotechnology from 2006 onwards. Green nanotechnology is an offshoot of Green Chemistry and Green Engineering that emerged from the participation of several national and international groups. Green nanotechnology, according to Chowdhury et al. (2021), advocates the replacement of existing products to produce new nanoproducts. The development of novel nanoproducts benefits the environment.

Types of nanoparticles

Metal nanoparticles

These nanoparticles are made from precursor metals. Metal nanoparticles can be made by photochemical, electrochemical, or chemical methods. To create metal nanoparticles, chemical reducing agents are utilized to reduce metal-ion precursors in the solution. These have high surface energy and may absorb very small molecules. These particles could be employed in a variety of applications, including research, biomolecular detection and imaging, environmental and bioanalytical analysis, and more. A sample is coated with gold nanoparticles before it is examined in scanning electron microscopy (SEM). This is done frequently to aid in the production of high-resolution SEM pictures by increasing electrical flow.

Sarraf et al. (2022) have reviewed metal/metalloid-based nanoparticles on the tolerance of plants to diverse types of abiotic stresses. According to Chen (2018), plant roots can accumulate metal-based NPs and then move them to various other areas of the plant. Plants, their interactions with NPs, and metal-based NP characteristics are all significant factors in NP translocation. Even while some metal-based nanoparticles have been found to have a positive impact on plant growth, unwanted NPs that end up in edible plant parts could be dangerous for human health. The phytotoxicity of NPs is caused by the release of harmful ions from NPs, radical production as a result of NPs as they interact with plants or the environment, or direct particle-to-plant contact.

Dimkpa et al. (2017) assessed the impacts of zinc nanoparticles (ZnNPs) on sorghum production, macronutrient utilization efficiency, and grain Zn enrichment. Under “low” and “high” amounts of nitrogen, phosphorus, and potassium, amendments were made through foliar and soil channels (NPK). Both forms of Zn considerably ($p \leq 0.05$) enhanced grain yield in soil and foliar additions, although soil-applied Zn at low NPK did so insignificantly. Zn enhanced N and K accumulation throughout NPK levels and Zn exposure pathways. Their findings point to a nano-enabled approach for improving grain nutritional quality, agricultural productivity, and the efficiency of nitrogen use, based on Zn micronutrient supplements, which may have beneficial impacts on both human and environmental health.

According to Singh et al. (2018), Mn nanoparticles administered to wheat by foliar exposure or soil addition did not affect vegetative or reproductive growth. Additionally, compared to conventional Mn fertilizers, Mn nanoparticles significantly decreased Mn accumulation in shoots while increasing the translocation efficiency in grains due to their higher reactivity and non-toxicity and due to the slower, continuous availability of soluble Mn from Mn nanoparticles as opposed to ionic Mn salt. Greater photophosphorylation and oxygen evolution in the Mn nanoparticles compared to bulk Mn indicates that this metal may have unique potential as a nano regulator of the photochemical pathway in agriculture (Predoi et al., 2020). Additionally, Mn nanoparticles are thought to stimulate metabolic processes like the generation of alkaloids in plants as well as plant growth. Plants can have cross-tolerance between abiotic and biotic stressors, and in this regard, stress tolerance might allow plants to develop faster and more resistant to subsequent environmental changes. In infected soils, foliar exposure to Mn oxide nanoparticles decreases disease by up to 28% compared to controls. The root of the plant is transported through the vascular system as part of the proposed mechanism for the dispersion of Mn nanoparticles throughout the plant. This process is regarded as active transport as long as it also involves signaling, recycling, and control of the plasma membrane.

In the case of waterweed (*Elodea densa* Planch), copper nanoparticles reportedly boosted plant photosynthesis by 35% at low doses (<0.25 mg L^{-1}) (Predoi et al., 2020). The development of 15-day lettuce seedlings was boosted by up to 91% by utilizing soil amendments containing up to 600 mg kg^{-1} of metallic Cu nanoparticles without producing any toxicity. The development of mung bean and wheat seedlings was toxically affected by metallic Cu nanoparticle concentrations up to 1000 mg L^{-1}, and zucchini biomass might be reduced by 90% compared to the control. Due to the influence of phytotoxicity at higher levels, the ideal concentration of aqueous copper for healthy plant development is in the range of just 0.02 mg L^{-1}.

Semiconductor nanoparticles

Semiconductor nanoparticles exhibit both metal-like and non-metal-like properties. Periodic table groupings of two to six, three to five, and four to six are used for their classification. In how they are altered, large band gaps in these particles cause them to operate differently. They are employed in water splitting, photonics, photocatalysis, and electronics, among other items. GaN, GaP, InP, and InAs are semiconductor nanoparticles in Group III-V, including CdS, CdTe, ZnO, CdSe, and ZnS as semiconductor nanoparticles in Group II-VI, as well as germanium and silicon which are semiconductor nanoparticles in Group IV.

Rizwan et al. (2009) revealed that ZnO-NPs positively stimulate the production of chlorophyll in corn and wheat. Singh et al. (2019) observed that ZnO-NPs have positive effects on the physiological and quantitative properties of Zea mays and *Triticum aestivum* L. This might be a result of its greater penetration into the leaf. ZnO-NPs have reportedly enhanced the antioxidant and phenolic compounds in *Capsicum annum* L. during seed germination (Garca-López et al., 2018). Chandhuri and Malodia (2017) found that ZnO-NPs significantly increased seedling development in nursery phases with foliar spraying of ZnO-NPs. A study on *Fagopyrum esculentum* revealed the presence of ZnO-NPs, which improved the antioxidant capabilities, photosynthetic effectiveness, and proline accumulation, thereby stabilizing the plant (Faizan et al., 2018). It is a novel fertilizer with special physicochemical features that increases crop output and food quality (Yusefi-Tanha et al., 2020). Studies on *Nicotiana benthamiana* have revealed that the plant uses ZnO-NPs to deactivate TMV (tomato mosaic virus) and activate its immunity (Cai et al., 2019). Higher crop output, lower disease severity, and increased plant resistance to a variety of microorganisms have all reportedly occurred by using ZnO-NPs (Tripathi et al., 2018). When used as a pesticide against the *Artemia salina* larva, zinc oxide nanoparticles (ZnONPs) showed great performance (Singh et al., 2018). In evaluating the fertility of ZnO-NPs during the development of *Arachis hypogea* plants, there were improvements in seed germination, along with quick shoot development, increased seedling vigor, improved root development, quick blooming, and rapid production. The fertility efficacy of ZnO-NPs in *Solanum lycopersicum* was tested and the findings revealed higher seed germination and high protein content (Rather et al., 2022).

Ceramic nanoparticles

By definition, ceramic nanoparticles are solids that are inorganic and are composed of phosphates, carbides, carbonates, as well as oxides. These nanoparticles have exceptional thermal resistance and are chemically inert. By altering their surface-to-volume ratio, size, porosity, and surface area, as well as other features, ceramic nanoparticles can be employed as potent drug carriers. These nanoparticles have been demonstrated to be an effective medicinal delivery mechanism for countering an array of illnesses, glaucoma, cancer, and bacterial infections.

Titanium oxide nanoparticles (TiO_2 NPs), as ceramic nanoparticles, have a variety of uses in agriculture. TiO2 NPs have surface characteristics that are frequently changed to improve their stability, heighten their beneficial effects, or lessen their toxicity. Their uses in the environment include the delivery of medicine, contaminant degradation, antimicrobial coating, and water purification (Yan et al., 2017; George et al., 2018). TiO_2 nanoparticles have been used to safeguard seeds, improve plant development and germination, combat agricultural illnesses, break down pesticides, and find pesticide residues. These NPs have also been linked to improvements in plant health, seed or product yield, and root and shoot growth. The synthesis of chlorophyll, the amount of soluble leaf protein and carotenoids, and the absorption of several crucial nutrients were all reportedly increased (Tan et al., 2017). TiO2 NPs were also used to dramatically reduce environmental stressors, such as drought in wheat (Mustafa et al., 2021) and high Cd levels in maize (Lian et al., 2020).

Polymeric nanoparticles

Due to the obvious production process, these nanoparticles might adopt the shape of nanospheres or nanocapsules. Even though a nanocapsule particle has a core-shell shape, a matrix-like structure can be found in nanosphere particles. In the former, the active chemicals and polymer are uniformly disseminated, whereas, in the latter, the active compounds are confined and contained by a polymer shell. To name a few benefits, polymeric nanoparticles offer regulated drug release, drug molecule retention, the possibility to merge therapeutic and imaging, and accurate targeting. They can be used for the delivery of medicine, in addition to investigative purposes. In the case of pharmaceutical administration, they are highly biodegradable and biocompatible.

In light of the issues with groundwater and surface water contamination brought on by agricultural runoff, the impact of polymeric nanoparticles on the transfer of agrochemicals from soils is also of interest. It is important to find the extent to which entrapment or encapsulation either improves or decreases the release of agrochemicals from soils. For instance, solid lipid nanoparticles and polymeric and PCL nanocapsules loaded with fungicides, namely, carbendazim and tebuconazole, resulted in less soil leaching than commercial formulations without nanotechnology (Shakiba et al., 2020). When paraquat was loaded into chitosan/tripolyphosphate and alginate/chitosan nanoparticles, Macedo et al. (2019) reported lower levels of adsorption for paraquat into soils, and Pereira et al. (2019) reported deeper penetration of atrazine into soil columns when loaded into PCL nanocapsules. According to Petosa et al. (2017) and Kah et al. (2018), the kind of polymer as well as the surrounding environment can have significant impacts on the transport or deposition of polymeric nanocarriers and the active components that accompany it (e.g. medications or herbicides) in water chemistry and soil type. The potential for naturally existing macromolecules, including proteins, polysaccharides, and organic materials, to bind to the nanoparticles and alter their transport behavior, should also be taken into account (Shakiba et al., 2020). While Chen et al. (2015) found that negatively charged humic acid had a significant effect on the deposition of positively charged poly-IJcaprolactone-b-ethylenimine) (PCL-PEI) as nanoparticles onto silica surfaces, the results were consistent with charge neutralization and reversal. Macedo et al. (2019) found that aquatic humic substances did not affect the colloidal stability of paraquat-loaded chitosan nanoparticles.

Numerous studies have shown the advantages of polymeric nanocarriers in lowering the toxicity of synthetic pesticides against non-target crop species (such as *Zea mays* or *Phaseolus vulgaris*) or environmental test organisms like *Caenorhabditis elegans*, *Allium cepa*, and *Pseudokirchneriella subcapitata* (a species of alga). Given the crucial role played by the microbial community in the cycling of nutrients and carbon in soils, or in the consumption of food and control of digestive disorders for oral medication administration in animal health applications, the impacts of nano-formulations on the microbiome are also of interest for applications in complex matrices (Shakiba et al., 2020).

Lipid nanoparticles

Spherical in shape, lipid nanoparticles range in size from 10 to 100 nm. The configuration is made up of a lipid-based solid core and a soluble lipophilic molecular matrix. Surfactants and emulsifiers assist in maintaining the stability of the outer cores of these nanoparticles. With the potential of being used as drug carriers and in delivery mechanisms, these nanoparticles can benefit cancer treatment through RNA release. While nanotechnology is still in its early stages of development, according to current figures, knowledge of nanotechnology is growing at an exponential rate.

Lipid nanoparticles are another interesting carrier system that may be utilized to transport nonpolar chemicals whose movement is constrained by contact with the lipids, leading to changed release patterns (Borges et al., 2020). These carrier systems provide several benefits, including the need for fewer active agents and smaller amounts of loss from leaching, degradation, and volatilization, as well as fewer negative environmental effects. Since the matrices are made up of lipids that are found in many species and low-toxicity polymers, including poly(ε-caprolactone), the major benefits of using lipid nanoparticles in agriculture are their low levels of toxicity. Several fungicide carrier systems have reportedly included cyclodextrins encasing carbendazim, silica nanospheres carrying tebuconazole, hydrogels, and spheres utilized as carriers for thiram, and polymeric microparticles containing tebuconazole (Dhiman et al., 2021).

Application of nanoparticles

Detection and control of plant diseases

By targeting pathogens, nanoparticles may be effective in the treatment and monitoring of food crop illnesses (Nile et al., 2020). Nanoparticles such as carbon nanoparticles, silver nanoparticles, silica nanoparticles, and alumina silicates are used for combating crop diseases. According to Ramezani et al. (2019), nanosilver is the most commonly used nanoparticle in biological systems. The capsulated nano-silver kills bacteria in soils and protects plants from a variety of illnesses.

Food crop production

Food security is one of the most pressing concerns in all countries. By 2050, the global demand for food and nutrition will have increased by 70% from current levels in a gradual manner (Tripathi et al., 2018). To face the future difficulties of agriculture-based food production, farmers will need new and creative technologies and will have to optimize current farming practices (Tripathi et al., 2018).

Several investigations have been conducted to see if nanotechnology can assist in the identification of chemical and biological substances in various food crops (Alfadul et al., 2017). One such method for preserving and storing food is an edible coating with encoded nanoparticles. Fruits and vegetables that have been coated with fresh food stay edible during storage and transit. As transportation and storage times increase, the active respiration processes may result in significant postharvest losses as well as poor nutritional and aesthetic quality of items. Controlling such nutrition and weight loss is critical for increasing the shelf life of fresh food products (Xiaojia et al., 2019). Temperature and relative humidity are two major issues. Together, they affect the microbiological activity and the respiration of fresh food.

According to Singh et al. (2017), nanosensors or nano-biosensors are utilized for a variety of purposes, including the measurement of readily available food elements, the detection of pathogens in processing facilities or food material, and warning consumers and distributors about the safety status of food. The nanosensor serves as an indication that reacts to alterations in environmental factors like humidity or temperature in storage rooms, microbial contamination, or product deterioration.

Nano-fertilizers

Utilizing nano-fertilizers instead of traditional fertilizers can help regulate the flow of nutrients in the soil and prevent losses that may occur due to chemical fertilizers (Tripathi et al., 2018).

Nutrients can be entrapped using nanomaterials covered with a thin layer or given as emulsions in nano-fertilization. The gradual release of nutrients from nanoparticle-coated fertilizers improves crop nutrient use. Iqbal (2019) examined the effects of nano-fertilizers on agriculture sustainability. Several additional researchers suggest that nano-fertilizers may be used as a low-cost, small-quantity alternative to traditional fertilization techniques (Kaila et al., 2021; Liu et al., 2021).

Nano-pesticides

The term “nano-pesticide” refers to an agrochemical combination that is used for solving difficulties in traditional pesticide management (Tripathi et al., 2018). Surfactants, organic polymers, and mineral nanoparticles are all in the nanometer size range and are employed in the creation of nano-pesticides (Alfadul et al., 2017). The next generation of nano-pesticides will be insect-specific in action while causing no harm to other insects in the soil.

Nano-sensors

Proper agro-climatic conditions are required for crop growth. Plant infections must be detected quickly and sensitively to protect crops effectively. Nano-sensors can be used to monitor soil fertility and other agro-climatic parameters throughout agricultural fields (Alfadul et al., 2017). Such techniques will result in increased agricultural yields at a very low cost of production. Researchers are developing nanosystems for releasing fertilizers and insecticides in response to agro-climatic conditions detected by nanosensors (Tripathi et al., 2018).

Interactions of NPs with the environment

With the immense rise in the use of nanoparticles, substantial numbers of nanoparticles are released into the environment, where they are most likely to be found in aquatic and terrestrial ecosystems. One of three methods may be used to release nanoparticles into the environment: spontaneously, accidentally, or purposely. Forest fires, volcano eruptions, clouds, dust storms, soil erosion, and ocean sprays all produce natural nanoparticles. Metal smelting, welding, mining, smoking, fissile fuel-burning, vehicle exhaust, and industrial waste, all produce unintentional nanoparticles. Their physicochemical features (e.g. surface chemistry, chemical composition, surface charge, size distribution, particle size, crystal structure, shape, porosity, and agglomeration state) determine their eco-toxicity (Rasmussen et al., 2018). The optical characteristics of nanoparticles are responsible for certain frequent challenges, like air visibility. Particles from diesel absorb a lot of light because of the black carbon concentration, which can exacerbate global warming. Engineered nanoparticles are made to be employed in various procedures and materials (Avila-Quezada et al., 2022). Depending on how these nanoparticles are used, they may be released into the environment in a variety of ways.

Plant interactions with NPs

Plants are one of the most basic features of the environment, and they serve a significant role in sustaining equilibrium throughout the ecosystem. Minerals and nutrients are transported across the food chain and food web. To navigate NPs in all of the indicated routes, higher plants work in tandem with soil, water, and environmental chambers (de la Rosa et al., 2017). Plants have been exposed to metallic and organic nanoparticles (NMs) produced from natural sources throughout their history (Siddiqi et al., 2017). Nevertheless, the growing synthesis and usage of ENMs in a variety of disciplines has led to an enhanced increase in plant exposure to NMs, both intentionally and unintentionally.

Table 1. Application of selected NPs in crop improvement

S/N	NPs	Plant species	Application	Effects
1	TiO_2	*Linum usitatissimum*	Leaf treatment	Increased carotenoids and chlorophyll content, decreased MDA activity and levels of H_2O_2
2		*Triticum aestivum*	Amended soil	Improved seedling dry weight, antioxidative enzymes, relative water content, total chlorophyll and carotenoids, transpiration rate and stomatal conductance.
3	ZnO	*Abelmoschus esculentus* L. Moench	Folair application	Increased SOD and CAT activity, and photosynthetic pigments, reduced proline and total soluble sugar contents
4	SiO_2	Strawberry	Exposure in nutrient soil	Increased chlorophyll, epicuticular wax layer, proline and leaf relative water content.
5	$FeSO_4$	*Helianthus annuus* L. cvs. Alstar, Olsion, Yourflor, Hysun36, and Hysun33	Foliar spray	Increased leaf area, shoot dry weight, sub-stomatal CO2 concentration (Ci), chlorophyll content, Fv/Fm, iron (Fe) content, and decreased sodium (Na) content.
6	Fe_3O_3	*Dracocephalum moldavica* L.	Foliar application	Increased leaf area, flavonoid, and anthocyanin content, as well as enhanced catalase, ascorbate peroxidase, and guaiacol peroxidase activity
7	AgNPs	*Triticum aestivum*	Potting soil	increased: number of leaf, leaf area, number of roots, root and shoot length
8		*Triticum aestivum*	Seed priming	Improvements in POD activity, proline, and sugar concentration, decreased antioxidative enzyme activity
9	CuNPs	*Zea mays*	Plant priming	Increased plant biomass and leaf water content, as well as anthocyanin, chlorophyll, and carotenoid concentrations; total seed number; and grain yield
10	MnNPs	*Capsicum annuum* L.	Nanopriming	Involves managing plant salt stress in promoting sustainable agriculture.

Source: Adapted from Mittal *et al.* (2020)

Plant species have diverse physiologies, which has led to variations in their uptake of nanoparticles. According to Pérez-de-Luque (2017), crop species from different botanical families treated with titanium dioxide, and magnetic carbon-coated, or gold nanoparticles revealed variations in the absorption and accumulation models in plants. The techniques of application, on the other hand, are crucial in deciding how well a plant can internalize nanomaterials. According to Barthlott et al. (2017), roots are built for food and water absorption, whereas leaves are meant for gas exchange and have a cuticle that prevents objects from penetrating.

Uptake of NPs by plant absorption

The possibility of an NP being absorbed is influenced by several factors. The nature of NPs, how NPs interact with plants, and plant physiology are all involved in absorption. According to research in physics, larger NPs reportedly aggregate in the apoplastic region. Plasmodesmata and other symplasts, on the other hand, allow smaller NPs to get through. Pore clogging and covering of the cell surface cause mechanical wear and tears, widely characterized for NP toxicity effects on plants (Pérez-de-Luque, 2017). Plants absorb NMs predominantly by the following pathways:

Root uptake. Due to their charge selectivity and high availability in soil, plants mainly absorb NPs through their roots. Root uptake activity and distribution, on the other hand, appear to be relatively slow (Avellan et al., 2017).

Leaf uptake. By passage through the hydrophilic or lipophilic pathways, NMs flowing through the plant via foliar absorption must pass through the cuticle barrier (Pérez-de-Luque, 2017). In the case of the hydrophilic route, polar aqueous pores sprinkled over the cuticles and/or stomata enhance the uptake of NPs with a size exclusion of 10 nm. Cuticular waxes, on the other hand, mediate the diffusion of lipophilic pathway-taken NPs. NP accumulates in the chloroplast nearly invariably as a result of these absorption pathways. As a result, metabolic processes in the cytoplasmic size exclusion are limited, and damage would be expected for the lateral variability of the stomatal foliar uptake pathway in aqueous solutes and water-suspended NPs. However, the following are some of the most important elements that influence plant NPs uptake:

Size. The size exclusion limit for nanoparticle penetration into plant tissues appears to be 40–50 nm, and there are reports on the maximum dimensions by which plants allow nanoparticles to move and accumulate inside the cells (Pérez-de-Luque, 2017).

Chemical composition. The uptake of NPs is also evaluated by the chemical makeup of the NPS and its interaction with the plant. Pea roots, for example, accumulate Fe-NP coated with carbon at a faster rate than wheat and sunflower roots. Translocation of these NPs to aerial parts has also been detected in wheat and pea, compared to the case of tomatoes and sunflowers (Pérez-de-Luque, 2017).

Functionalization. Coating a nanomaterial surface can drastically modify its characteristics for plant uptake and accumulation (Pérez-de-Luque, 2017).

Morphology. According to several studies, the shape of nanoparticles can affect NPS uptake in plants (Pérez-de-Luque, 2017).

Plant physiology. According to Pérez-de-Luque (2017), species of plants vary in their physiology, which contributes to variances in nanoparticle ingestion.

Route of NP exposure and uptake. Another variable that influences NP uptake kinetics is the route of administration or exposure. This factor influences how well a given NP internalizes. Leaves are often immune to a wide range of chemicals, including NPs, because they act as a channel for gas exchange in plants. Roots, on the other hand, are involved in water and nutrient absorption, making them better suited to NP absorption (Pérez-de-Luque, 2017).

NPs transport to plant cells

The route taken by NPs transport within plants is crucial since it determines the accumulation and toxicity of diverse plants. NPs that travel through the phloem, for example, tend to accumulate in organs such as grains and fruits. Also, it has been observed that NPs migrate between the xylem and the phloem, showing that translocations may not be confined to a specific type of cell. Intracellular and extracellular pathways are used for movement and different plant-NP interactions. Extracellular routes, such as xylem arteries, extracellular spaces, and walls of cells of nearby cells are involved in apoplastic transport. Symplastic transport is usually based on plasmodesmata that distribute chemicals and water between nearby cells, their cytoplasms, and sieve plates (Pérez-de-Luque, 2017). The following is a description of these movements:

Apoplast. This type of mobility is essential because it helps NPs move widely across plant tissues (Yan and Chen, 2018). It allows NPs to access the central cylinder of roots and vascular tissues for upward transfer to the aerial sections of the plant only through the xylem, which leads to the transpiration stream. NPs, on the other hand, reach the Casparian strip after passing through the xylem, which must be accessed via endodermal cells via the symplastic pathway. As a result, the Casparian strip has a higher accumulation to deliver NPs in a regulated manner (Pérez-de-Luque, 2017).

Symplast. The phloem sieve as tube elements, sieve plates, and plasmodesmata structures, all permit material and flow of water among adjacent cells. The symplastic system is involved in this absorption mechanism, which represents another route for NP entrance. Many NPs reportedly translocate through the symplastic process. This technique allows for the NPs distribution across organs and non-photosynthetic tissues of plants (Pérez-de-Luque, 2017). The following are some examples of symplastic mechanisms:

Endocytosis. NP encapsulation can occur when the plasma membrane is invaginated within it, providing another mode of NP transport (Etxeberria et al., 2016).

Pore formation. Damage to the plasma membrane may result in the creation of a pore that allows NPs to penetrate the cell. This way of entrance allows the NP to proceed freely through the cytosol without being impeded by any organelle (Wong et al., 2017).

Carrier proteins. NPs binding to neighboring proteins, such as those found in the cell membrane, may also aid internalization (Behzadi et al., 2017). Aquaporins are hypothesized to be NP carriers inside the cell. However, owing to their modest pore size, which ranges between 2.8 and 3.4A, the rates of absorption and transportation are usually limited (Abhijeet et al., 2021).

Plasmodesmata. Another mechanism for NPs to enter the cell is via plasmodesmata, which are structures specialized for transfer between cells. This process facilitates NP translocation across the phloem. However, for an efficient translocation, the NMs must already be in the symplast (Pérez-de-Luque, 2017).

Ion channels. These have been suggested as one of the possible pathways for NPs to enter the plant. The ion channels are usually 1 nm in size, which renders NP transport through them unlikely. As a result, in traveling through these channels, NPs must undergo considerable changes (Abhijeet *et al*., 2021).

Engineered distribution of NP to plant cells

Endocytosis via aerosol and drop-cast procedures are among the most effective methods of delivering drugs and NPs inside specific cell organelles. Pore creation, on the other hand, is effective in achieving delivery in the cytosol (Avila-Quezada et al., 2022). Additionally, other microorganisms, such as bacteria or fungi, could be used for developing new strategies for delivering and translocating NMs that are otherwise impermeable across plant cells. These strategies can be utilized to manage the penetration of NPs into plant cells by antimicrobial drugs and crop systemic illnesses (Wang et al., 2017; Lee et al., 2019).

In soybean, ZnO reportedly had contradictory effects, increasing root length while shrinking the root tip and inhibiting root growth (Müller et al., 2021). According to Ikhajiagbe et al. (2021), silver nanoparticles (AgNPs) also improved morphological growth characteristics, such as root growth.

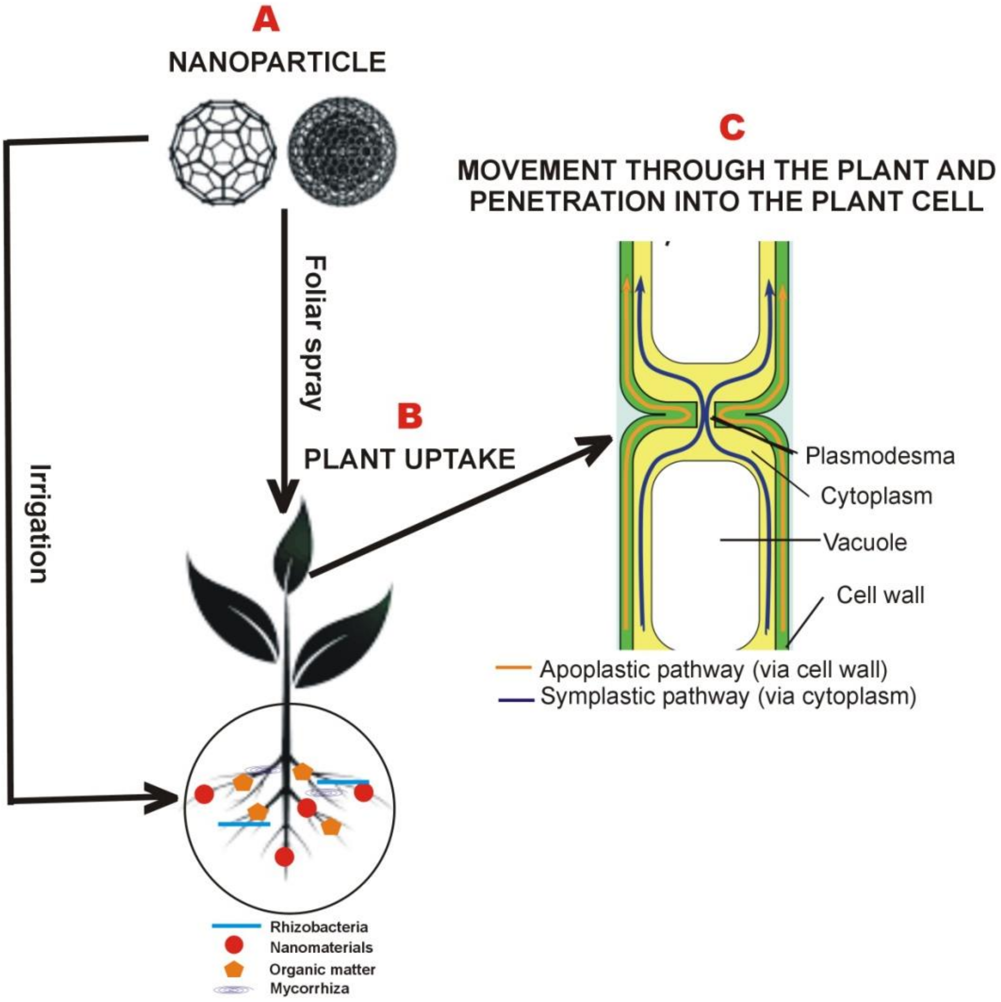

Fig. 1. Factors that influence NP absorption, distribution, and permeation in plants (A) The characteristics of NPs influence how they are absorbed and transported in plants, as well as how they are applied. (B) NPs in the soil can interact with microbes and chemicals, facilitating or inhibiting absorption. (C) Nanomaterials can migrate up and down the plant using the apoplastic and/or symplastic routes. Endocytosis, pore formation, carrier protein-mediated pore formation, and plasmodesmata have all been postulated as processes for NP internalization within cells.

NPs interaction with food

Plants are among the most basic environmental components, and through transferring nutrients and minerals, they serve a crucial role in playing with the maintenance of ecological systems, such as the food chain and food web. Higher plants establish a network using their water, soil, and environmental compartments that enable NPs to move across all the allocated routes (Tripathi et al., 2017).

Food processing raises food standards and modifies food matrices to meet demands. One can depend on delivery systems such as nanoemulsion and nanoencapsulation for an effortless distribution of vital nutrients in the diet, which results in uncomplicated absorption in the body owing to their small size (Choi and McClements, 2020). Nano-delivery methods improve the bioavailability of active compounds, the precise release tendency of active compounds, and the shelf life of active compounds. A variety of undesirable solutes combine with food during processing, and separating them takes a lot of effort and time. However, nanofiltration makes it simple to separate undesirable solutes. Nano filters contain membranes that are highly permeable to salts but less permeable to organic solvents such as proteins and other biomolecules (Cao et al., 2021). Nanofiltration is based on the notion of electroneutrality. Pore size and charge density are two factors that influence nano filters. Nano filters are often used in dairy products to separate undesirable solutes from economically relevant solvents such as milk (Khan and Selamoglu, 2020). Food deterioration, owing to oxidation, is aided by the browning reaction and is a primary cause of multimillion-dollar food loss. The use of oxygen scavenger films made by Gaikwad et al. (2018) and Mohammad et al. (2022) using nanotechnology can prevent such losses. These films are made of TiO2 NPs that react with various organic polymers to maintain a low oxygen level, thereby preventing rancidity. Nanotechnology has a big role to play in boosting enzyme activity. Enzymes with nanoparticles are resistant to denaturing chemicals like proteases (Sharma et al., 2017). Ahmad et al. (2019) described the use of AgNPs to immobilize glutamate dehydrogenase and lactose dehydrogenase. Sharifi et al. (2020) provided an opinion on the stability of enzymes immobilized on NPs, stating that incorporating NPs into enzyme transporter systems preserved or yet improved the activity of immobilized enzymes.

Future perspectives

Green nanotechnology has the potential to improve the efficiency of agricultural inputs dramatically, making nanoparticles an important tool for ensuring long-term developments in agroecosystems. Agrochemical encapsulated nanocarrier systems, nano pesticides, nano fertilizers, nanoherbicides, and other agricultural nanotechnologies have all been created in this field. Higher crop yields, plant disease reduction, as well as weed and insect elimination with less cost, energy, and waste production are all potential agricultural benefits.

Plant development and crop yield are both aided by nano-derived agricultural commodities. Because of several characteristics, such as compact size, long-term storage, ease of transport, convenience in handling, high effectiveness, and non-toxicity, farmers prefer this option to traditional pesticides and methods. The commercialization of green nanotechnology is gaining popularity everywhere around the globe. The following are a few of the emerging nanoparticle developments in agriculture:

Nano-plant growth boosters

The dormancy of seeds is a significant issue that reduces agricultural productivity. Multiwalled carbon nanotubes, which cause pores to form in the tough seed coat, can be used as a remedy for this problem. As a result, water is absorbed into the seed coat. A greater value of chlorophyll index was reported for crop plants treated with nanomaterials (Etesami et al., 2021; Safdar et al., 2022). Shinde et al. (2020) reported that green-produced magnesium hydroxide nanoparticles [Mg(OH)2NPs] exhibit 100% germination rate capacity for *Zea mays* growth *in vivo* and *in vitro*. Similarly, the usefulness of AgNPs was examined *in vitro* using seedling development of *Boswellia ovalifoliolata*, which grew to a maximum height of 10.6 cm (Savithramma et al., 2012). Surprisingly, the nano-primed seed is becoming more popular as a way to improve seed germination. According to Mahakham et al. (2017), nano-priming by AgNPs causes germination of seed in addition to nanopore creation for better water uptake, cell wall loosening by hydroxyl radical production, rebooting ROS/antioxidant systems, and hydrolysis of seed starch via nanocatalyst. Ikhajiagbe et al. (2021) revealed that AgNPs increased plant yield by massive amounts in ferruginous soil, a circumstance that has hitherto been detrimental to rice yield disposition.

Nanofertilizers

Nanomaterials are used for restoring inadequate soils and provide a smart, one-of-a-kind, ecologically-friendly, and long-term solution. According to Alsharef et al. (2016), incorporating 0.2% multiwall carbon nanotube (MWCNT) and carbon nanofiber (CNF) into clay-sand soil (UKM soil) improved hydraulic conductivity and reduced soil fracture.

Nanoparticles also boost the essential nutrient bioavailability in plants. Cai et al. (2018) evaluated the effects of magnesium oxide nanoparticles (MgONPs) on tobacco plants at concentrations ranging from 50 to 250 g/mL, while observing changes in the root, leaves, and shoot morpho-physiological features for the duration of absorption and build up. Green nanotechnology can be used for making food products more hygienic, resulting in a healthier lifestyle for the populace. Cai et al. (2018) developed nanoclays which, in conjunction with standard fertilizers, may keep nitrogen in the soil and prevent nutrients from seeping into deeper layers. Furthermore, engineered xylem vessels are the best methods for examining various kinds of pathogenic populations that affect the host body, and they also enable us to research the physiochemical and biological interactions among plants and the parasites that affect them (Santos and Olivares, 2021).

Nanopesticides

The production and application of pesticide organic nanoparticles is a viable solution to this problem. Chemical pesticides have contaminated the environment as a result of their misuse. Nanoparticles can replace chemical pesticides because they are more soluble, durable, and disintegrate quickly by not leaving hazardous residues in the soil. To make these nano-based herbicides, active compounds like atrazine can be mixed with poly (epsilon-caprolactone) nanoparticles (Chaud et al., 2021). For example, fungal infections can be found in wheat, rice, and maize. Nanoparticles can help remedy this problem by being particularly effective against a range of fungal assaults. For instance, AgNPs have reportedly been efficient against *Magnaporthe grisea* which is responsible for rice blast disease, whereas copper nanoparticles were reportedly effective against *Botrytis cinera* (Nandini and Geetha, 2021). Similarly, ZnONPs and MgONPs are particularly effective against *Mucor lumbeus* (Yaghubi Kalurazi and Jafari, 2021).

Nanoherbicides

Getting rid of unwanted weeds is one of the most serious threats to farming. Numerous chemical herbicides can inhibit the runoff development of these weeds because all of those chemical-based herbicides are believed to have persistent toxicity, although in minute quantities. As a result, nanoherbicides are used as safe agents in averting such a catastrophe (Baker et al., 2017). Crops can detect harm when there is excessive herbicide use. Herbicide residues can be left in the soil when substantial amounts of herbicides are employed. As a result, the repeated use of an herbicide inevitably leads to herbicide resistance in weeds, leading to a change in plant physiology. Herbicides for broadleaf and grassy weeds have a half-life of nearly 125 days and are mobile in some soils. A pesticide, Atrazine, can be used for controlling certain types of weeds. This s-triazine-ring herbicide is used all over the world for weed control, but it is currently in jeopardy due to residual issues (Aslam et al., 2022). Bioavailability, chemical stability, photodecomposition, solubility, and soil sorption have all been reported as features of nanoherbicides.

Research suggests that combining nanoparticles with active chemicals like atrazine and using poly (epsilon-caprolactone) nanoparticles as the transporter enhances herbicidal activity (Chaud et al., 2021). Furthermore, by encapsulating herbicides with sodium triphosphate and chitosan nanoparticles, researchers were able to diminish herbicide sorption and, thus, reduce environmental risk (Ghaderpoori et al., 2020). Gabriel Paulraj et al. (2017) reportedly cross-linked chitosan nanoparticles with diuron disulfide to control herbicide, probably due to glutathione content. The outcomes were effective in stimulating plant growth while lowering toxicity.

Agrochemical encapsulated nanocarrier systems

Agrochemical agents are often used for protecting crops from pests (harmful insects, pathogens, parasitic weeds) that lower output and productivity. They can also be used for diagnosing soil and plantation strength, managing fisheries, and regulating livestock management. Nonetheless, the uncontrolled use of pesticides in the fight against harmful pests and insects has suppressed output, causing disease and insect resistance, increasing demand for new agrochemicals, and worsening environmental imbalances (Chaud et al., 2021).

The application of nanotechnology-based delivery methods has presented the exceptional potential to revitalize agronomic practices due to the regulated, controlled release of fertilizers and agrichemicals essential for boosting crop output (Prasad et al., 2017). Such systems are crucial in agriculture, as they improve the effectiveness of fertilizers and agrochemicals (Sampathkumar et al., 2020).

Although nano pesticides appear to have a promising future in agribusinesses, human exposure to agrochemicals can be dangerous because the molecules can pass through biological membranes and may irreversibly harm key organs. The risks that are associated with hazardous nano pesticides, which could also cause toxic and genotoxic events, are currently being considered by analyzing the effects of nano pesticides and their physicochemical properties, such as size, electrical charge, and surface properties, not only on the chemical makeup of the metal matrix but also on the chemical structure of the base material (Zieliska et al., 2020).

By lowering the required dose/Ha and reducing herbicides and agrochemicals with a high leaching rate in the soil, the function of polyelectrolyte complexes, as transporters of nano pesticides are deemed important by urban and rural farmers. The siliceous-based formulation of the MCPA herbicide has reportedly reduced environmental concerns, compared with the standard formulations of MCPA (Chaud et al., 2021).

Other agricultural nanotechnologies

Nanotechnology could be a viable alternative to better recycling agricultural waste. Agri-wastes can be used for making nanoproducts if they are processed properly. Furthermore, postharvest methods for the production of nanocomposites, nano cellulose, biochars, and other materials from agricultural wastes have yet to be implemented effectively. The best examples are nano-lignocellulosic materials, which are made up of a combination of nanoparticles, lignin, and plant cellulose. Cellulosic crystals on the nanoscale can be employed in polymer matrices as a lightweight augmentation for construction and packaging (Trache et al., 2020). Michigan Biotechnology Incorporated was the first to create wheat straw (MBI) for making cellulosic whiskers. When compared to fiberglass and plastic, nano cellulose is a prudent alternative. The most significant advantage is that nano cellulose is biodegradable, making waste management convenient (Goh et al., 2021). Interestingly, after harvesting, 110 million tons (Mt) of wheat and 12 Mt of rice husks were created as waste, which appeared as a good, unprocessed material for nano-silica, renewable energy, and biochar, as well as other products with added value (Singh et al., 2019). The technological performance of these waste masses can be employed to produce nano-silica employing nanotechnology methods, paving the way for the best solution to the disposal problem (Saleem et al., 2021).

Other uses

Nano-based identification tags (barcode technology) are also employed in agriculture. Barcodes have several advantages, including the capacity to be quickly coded, tracked, and expanded for lifespan. These barcodes serve biological as well as non-biological purposes (Bock et al., 2022). Biological barcodes are employed in intracellular histopathology, as identification tags, and have a low-cost process for the identification of pathogens in food products (Hernández-Cortez et al., 2017). Animal husbandry and agricultural products use non-biological barcodes as trackers. Quantum dots NPs are composed of semiconductor metals like cadmium, silicon, and indium. They are used for identifying diseases like witches broom in lemons caused by *Phytoplasma aurantifolia* (Rad et al., 2012). These are contemporary pathogen detection technologies. In the past, staining methods were utilized for pathogen identification, but were quite expensive. Quantum dots have several characteristics, including efficient luminescence, narrow emission spectra, and great photostability (Warad et al., 2004). Bandyopadhyay et al. (2013) reported the use of QDs as a fluorescent marker in conjunction with immunological magnetic separation to identify *E. coli* 0157:H7. Anti-*E. coli* 0157 antibodies formed complexes with target bacteria, allowing *E. coli* 0157:H7 to be identified quickly. Although a variety of NPs has reportedly shown antimicrobial action, only a handful of them (e.g. TiO2NPs, AgNPs, ZnNPs, and ZnO NPs) is commonly utilized as microbial inhibitors in plant tissue culture. Su et al. (2004) investigated the fungicidal and bactericidal capability of new-age revolutionary nanomaterials such as quantum dots, nanotubes, carbon polymer dendrimers, nanoclusters, and others in plant tissue culture.

According to Naseer et al. (2018), years of research have proven that nanoscale materials have significantly diverse characteristics and unanticipated behaviors. Thus, concerns exist about its toxicity. Engineered nanoparticles have yet to be adequately examined in their interactions with numerous biological beings and the environment.

Challenges and health implications of NPs in agriculture

The deliberate use of nano-sized materials in agricultural pursuits may have unforeseen health consequences (Iavicoli et al., 2017; Neme et al., 2021). In this case, residues of nanomaterials in crops and soil are likely to increase environmental and human exposure, with exposure channels including probable bioaccumulation in the food chain and the environment.

Materials at the nanoscale, according to Naseer et al. (2018), have significantly different characteristics and unanticipated behaviors. Engineered nanoparticles have yet to be adequately examined in their interactions with numerous biological beings and the environment. Yu et al. (2020) took a big step in the right direction by conducting a thorough investigation of how nanomaterials can cause oxidative damage in cells. The study largely aimed at figuring out the mechanism and, as a result, compared the probable toxicity of diverse nanomaterials. This can be achieved basically by observing how reactive species are produced within the cell. The difference between oxidants (peroxide, ROS, etc) and antioxidants causes oxidative stress (glutathione, vitamin C, etc.). A rise in the number of oxidants in a cell can be harmful to that cell. There is a lot of research on how pollution particles like carbon soot and other nano-sized pollutants produce reactive oxygen species (ROS) and cause oxidative stress (Niranjan and Thakur, 2017). According to Yu et al. (2020), by comparing the oxidative stress systems of traditional particles with new particles that are produced daily, the information can be generalized to newer materials. This and other comparable investigations, if thoroughly thought out, can function as an essential building block toward a more resourceful nanotoxicology screening system. Even though the study sheds light on the oxidative harm that certain nanomaterials can produce, it leaves a few questions unanswered. To begin, tests should be performed on multiple cell lines as well as primary cell cultures (such as human macrophages) to ensure that the cell culture pattern is failsafe. Second, several dose administrations should be examined by comparing doses to the dose of the nanomaterial emitted into the surroundings. Finally, other formulations of media must be evaluated, since the majority of studies have employed fetal calf serum (FCS), which includes significant levels of different antioxidants, and may conceal the oxidative damage induced by nanomaterials. Finally, but certainly not least, more assays must be performed to complete the bigger picture. However, intracellular and external oxidative stress, for example, must be evaluated. The field is still in its infancy, and there is a lot to learn. The fact that nanoparticles can alter lipid architecture and overall membrane structure (Behzadi et al., 2017) suggests that they may have a broad impact on biology. New empirical data are desperately needed to gain a better understanding of the interactions and processes between nanoparticles and biological systems. These interactions mostly involve biomolecules like proteins, whereas some cases of research have offered other ways to track them. Cardellini et al. (2022) focused on nanoparticle physical interactions and discovered that nanoparticles can affect lipid membrane phase structure. As a result, it would be premature to draw any inference or to favor a specific topic of study. For the time being, we can state that understanding how nanoparticles interact with biological molecules or living matter, whether physically or chemically, can provide a wealth of prospects on the subject of toxicity. The understanding and mechanism of oxidative stress appear to be the most appropriate criteria for distinguishing between hazardous and non-toxic compounds. Nanotoxicologists can have a near-term goal of developing further studies, based on recent work by Yu et al. (2020) and other comparable groups. This will aid the current understanding of the mechanisms underlying nanomaterial-induced toxicity and can contribute to the development of safe and commercial nanotechnology.

Naseer et al. (2018) reported that nanoparticles can cause oxidative stress in human body cells and can travel from the lungs to the bloodstream, cell nuclei, and the central nervous system, leading to gastrointestinal inflammation, Alzheimer’s disease, Parkinson’s syndrome, and DNA damage. Nanoparticles have been associated with detrimental effects on the liver, kidneys, and other vital organs after long-term exposure.

Conclusion

Green nanotechnology is an environmentally friendly and cost-effective agricultural technology that has the potential to increase agricultural productivity while reducing pesticide use. It has several applications in agriculture, including pathogen detection, nano-pesticide delivery to specific target sites, and improved nutrient absorption in plants. At the same time, it saves money on energy and protects soil and water resources. Nanotechnology applications have the potential to address future agricultural concerns like food security, especially in underdeveloped nations.

Conflict of interest statement

The authors declare that they have no conflicts of interest.

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