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Nanotechnology Enabled Advancements in Plant Breeding

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ABSTRACT: Nanotechnology consists of basic nanoparticles with small size to large surface area (1–100 nm) that have several potential functions. In a recent hybrid field known as nanobiotechnology, elements of both nanotechnology and biotechnology are combined, and it uses nanoparticles as basic tools for manipulation of plants and nanomaterials serve as carriers for genes and chemicals that activate gene expression and regulate genetic material inside plants, and there is a great deal of promise and depth to this technology's future advancement. Nanotechnology in plant breeding has potential but faces challenges. The long-term effects of nanoparticles on plants and the environment are unknown, requiring research for safety. Scalability and cost-effectiveness limit adoption, while ethical and regulatory concerns surround GMOs and gene introduction. Careful evaluation and regulation are needed for responsible and sustainable use. Through nanoparticles as a treatment, seeds can speed up germination, increases seedling strength, vigour and improve seed quality. The application of nanotechnology in plant breeding comprehends; disease and vermin control, seed technology, plant genetic modification, monitoring of plant growth stages, incitement of hormonal impacts, and precise farming. Nanotechnology also aids in the improvement of crop output in agriculture by reducing input losses and ensuring efficient nutrient and water management. Another breakthrough in nanotechnology for agricultural production improvement is the development of cultivars resistant to various insects through DNA transfer method in plants or nanoparticle-mediated gene transfer, respectively. Furthermore, this review examines several nanotechnological approaches in plant breeding and tissue culture, focusing on their current application and scanning the opportunities, potential benefits, and associated risks.

Keywords: Nanotechnology, Agriculture, Plant Breeding, Crop Improvement, Nanoparticles, Nano priming.

INTRODUCTION

The phrase "nanotechnology" was termed by Taniguchi and made popular in the 1960s by Dr. Richard Feynman (Bhau *et al.*, 2016; Reddy *et al.*, 2017). The study, creation, modelling, control, and use of useful materials, systems, and devices at the nanoscale are all considered aspects of nanotechnology. Between 1 to 100 nm is considered "nano" typically (Ndlovu *et al*., 2020; Sinha *et al*., 2017; Elizabath *et al*., 2019). This technology is connected to interdisciplinary fields including chemistry, biology, and other integrative fields (Elizabath *et al*., 2019; Kumari *et al*., 2018). It is one of the most promising tools that may increase agricultural potential through increased yields in an environmentally responsible manner, and that too in a difficult setting (Mishra *et al*., 2017). It may prove to be an effective tool for the complete understanding of numerous biological and physiological processes, such as cellular processes, control of characteristics, and the creation of genotypes resistant to biotic and abiotic influences to boost agricultural output (Ali *et al*., 2018).
Crop genomes have traditionally been the major target of nanotechnology to possibly improve plant types that are more resilient to diverse biotic and abiotic challenges (Prasad *et al*., 2017). Nanotechnology has proven to be an effective tool in the enhancement of plant growth, yield, and quality through the application of novel strategies in plant breeding (Ma *et al*., 2019; Liu *et al*., 2020; Wang *et al*., 2016). To enhance crops, identify plant disease, and keep track of plant health and soil quality, nanotechnology is seen to be necessary in the agricultural industry. These will eventually lead to improved plant performance, which is the primary goal of any breeding effort (Sertova, 2015).
The reaction of plants to nanoparticles is influenced by factors such as their size, concentration, physical and chemical properties, and composition, as noted by Siddiqui *et al*. (2015). Nanotechnology is seen as a promising avenue for advanced development in various fields, according to Tile *et al*. (2016). Alghuthaymi *et al*. (2021) suggest that nano-based technologies have great potential in agriculture, with the development of

powerful formulations that ensure optimal distribution of agro-nutrients, pesticides/insecticides, chemicals, and plant growth regulators for increased efficiency. The value chain of the entire agriculture production system may utilise nanotechnology. (Subramanian *et al*., 2011). According to recent research, graphene is a potential substance that may act as a transporter for plant nutrients. It can improve crop yield while having no negative environmental impact by releasing nutrients to the plants in a gradual, regulated manner (Kabiri *et al*., 2017). Publicly funded universities and research institutes are responsible for most of the nanotechnology research and development, except for a few exceptions, according to Bhagat *et al*. (2015).

This review paper provides a brief overview of the recent developments in nanotechnology-based plant breeding. As of 2022, research suggests potential concerns regarding the long-term environmental impacts of nanomaterials on plant health, soil quality, and agricultural sustainability are still limited. The accumulation of certain nanomaterials in plant tissues can potentially affect growth and physiological processes. Additionally, the interactions between nanomaterials and soil components may alter soil microbial communities, nutrient availability, and soil structure, which can have cascading effects on ecosystem functioning. The challenges and limitations of integrating nanotechnology into existing agricultural systems are important considerations that require further investigation. Up to 2022, research has indicated a need for in-depth analysis of the feasibility and scalability of nanotechnology-based solutions in real-world farming practices. This includes examining the practicality of implementing nanotechnology on a larger scale and assessing its compatibility with existing agricultural practices and infrastructure. Moreover, the cost-effectiveness of nanotechnology in agriculture needs to be evaluated to determine its economic viability for farmers and stakeholders.

Additionally, regulatory considerations play a crucial role in the adoption of nanotechnology in agriculture. The potential environmental and health risks associated with nanomaterials require a robust regulatory framework to ensure the safety and responsible use of these technologies. Research must focus on understanding and addressing any potential regulatory challenges and developing guidelines or standards to govern the application of nanotechnology in agriculture. Overall, the challenges and limitations surrounding the integration of nanotechnology into existing agricultural systems, including feasibility, scalability, cost-effectiveness, and regulatory considerations, require further investigation to facilitate its effective and sustainable implementation in real-world farming practices. Further research is needed to comprehensively assess the potential risks and benefits of nanotechnology in agriculture to ensure its sustainable implementation and minimize any unintended environmental consequences.

Role in plant breeding. By studying nanomaterials, nanotechnology is a key component in the creation of genetically enhanced crops (Servin *et al.,* 2015). To increase crop yield or disease resistance, improved genes can be identified using nanotechnology (Kerry *et al.*, 2017). Using genetic engineering or plant breeding, this approach aids in the development of resilient and better plant genotypes (Nikunj *et al.,* 2014). Plant breeding and genetic modification to create better crops frequently utilise nanotech-derived devices (nano-sensors and nanoparticles). (Kumar, 2020).

Nanobiotechnology. By using this technology to better understand the biology of various crops, breeders may be able to increase agricultural yields or nutritional value (Sah *et al*., 2014). Atomically altered seeds, plant cells with silica beaks, hormone and antibiotic delivery in plants, particle farming, and iron seeding are a few examples. (Weigl *et al.*, 2003; Prasanna 2007; Chinnamuthu and Boopathi 2009; Jha *et al*., 2011; Cursino *et al*. 2011). Particle farming is the process of cultivating plants in predetermined soils to produce nanoparticles for industrial purposes. Plant production and growth are negatively impacted by abiotic stress. Salinity and drought are the two abiotic stressors that affect plants the most widely (Lavania *et al*., 2015; Zhao *et al*., 2020). In this regard, the activities of antioxidant enzymes including chloramphenicol acetyltransferase (CAT), super oxide dismutase (SOD), and peroxidase are controlled by nanoparticles, which are particularly efficient at overcoming the dry circumstances (Zhao *et al*., 2020). As a result, it is now feasible to modify many new plants to resist abiotic stress in more sophisticated ways while also combining better and more desirable agronomic features through the integration of biotechnological and nanotechnological factors (Lavania *et al*., 2015).

Nanoparticle Mediated Gene Delivery. This method is becoming increasingly popular for delivering proteins and template DNA. It combines nanotechnology with genome editing technologies like CRISPR and Cas. In addition, this aids in more efficient and cost-effective food production (Ghouri *et al.,* 2020). Researchers have used various nanoparticles such as nanofibers, nano capsules, and nanoparticles to manipulate gene expression as noted by Agrawal *et al*. (2014); Rad *et al*. (2013). The CRISPR/Cas9 system is a revolutionary invention that will change biotechnological procedures, and the use of nanoparticles in its delivery significantly increases its specificity and efficiency for target genome editing, according to Mout *et al*. (2017).

Role in tissue culture. A nutritional medium is used in plant tissue culture to develop plant cells or plant components in a controlled sterile environment. Plant tissue culture faces a significant challenge from microbial contamination. Sources of contamination include the actual explants as well as the actual laboratory setting (Leifert *et al.,* 1994). Recent research has demonstrated that treating the surface of explants with nanoparticles greatly lowers microbial contamination in a variety of plants. It has been demonstrated that metal and metal oxide nanoparticles are helpful for the eradication of certain bacteria (Wang *et al.,* 2017).

Mahna *et al.* (2013) examined the impact of Ag NP treatment on the surface sterilisation of Arabidopsis seeds, potato leaves, and tomato cotyledons. It was discovered that treating the explants with 100 mg L^{-1} Ag NPs for 1–5 minutes was the best method for completely decontaminating the seeds, leaves, or cotyledons. This method also had no negative impact on the viability of the explants. In Murashige and Skoog (MS33) media, 50 mg L^{-1} Ag NPs greatly reduced microbial growth (Safavi *et al*., 2011). On MS medium with 1% (w/w) TiO_2 NPs, ideal outcomes were reached (Safavi *et al*., 2014). Silver nanoparticle use in plant tissue culture was recently evaluated by Sarmast and Salehi. Nanoparticles have been proven in several studies to have favourable impacts on callus induction, shoot regeneration**,** and growth. In a mixture containing 15 mg L^{-1} ZnO NPs and 3.0 g L^{-1} NaCl, callus development and plant regeneration in tomato plants were maximised (Alharby *et al*., 2016). Using MS medium supplemented with 5 mg L^{-1} BA, 3 mg L^{-1} NAA, and 8 mg L^{-1} Ag NPs, the frequency of callus production in *Solanum nigrum* increased to 89%, and the fresh weight of the callus increased to 4.67 g per leaf explant (Ewais *et al.,* 2015). Anwaar *et al.*, 2016 reported that adding CuO NPs (15–20 mg L1) improved organogenesis in rice cultivars. According to some reports, TiO_2 NPs may function in a manner akin to that of plant growth regulators (PGRs) such as cytokinin and gibberellic acid (Mandeh *et al.*, 2012).

Vijayakumar *et al.* (2010) revealed that, using a gene gun, carbon supported Au NPs transported DNA into *Nicotiana tabacum*, *Oryza sativa*, and *Leucaena leucocephala* more effectively than conventional gold particles. Pasupathy *et al.,* 2008 reported Poly (amidoamine) Dendrimer NPs were used to develop a novel gene delivery technique in plants. The authors were successful in delivering plasmid DNA encoding the green fluorescent protein (GFP) into turf grass cells. Recently, Kokina *et al.,* 2017 examined how soma clonal variation in *L. usitatissimum* was affected by Au and Ag NPs. Soma clonal variation was more common in Calli, and regenerated shoots grown on media containing Au NPs than Ag NPs. The plant's in vitro culture medium may function as a source of nutrients when nanoparticles are introduced. The total phenolic content of *Vanilla planifolia* shoots grown on MS medium supplemented with 25 and 50 mg L^{-1} Ag NPs increased significantly (Spinoso- Castillo *et al.,* 2017).

Mentha longifolia essential oil content increased by 2.226 and 2.19%, respectively, after application of Cu and Co NPs (Talankova- Sereda *et al.,* 2016). Zhang *et al.* (2013) studied the ability of Ag NPs to increase the amount of artemisinin in cultures of Artemisia annua hairy roots. Shakeran *et al.*, 2015 reported that in hairy root cultures of *Datura metel*, it was examined how biotic (Bacillus cereus and Staphylococcus aureus) and abiotic ($AgNO_3$ and Ag NPs) elicitors affected the synthesis of atropine. Moharrami *et al.*, 2017 examined the ability of Fe NPs (450–3600 mg L^{-1}) to trigger an increase in the levels of hyoscyamine and scopolamine in cultures of *Hyoscyamus reticulatus* hairy roots. The amount of essential oils in Mentha longifolia increased by 2.226 and 2.19%, respectively, after the application of Cu and Co NPs (Talankova-Sereda *et al.,* 2016). Raei *et al.,* 2014 noted that aloin concentration was considerably increased in aloe vera suspension cells exposed to 0.625 mg L^{-1} Ag NPs or 120 mg L^{-1} TiO_2 NPs for 48 hours. The MS medium containing 25 or 50 mg L^{-1} of Ag NPs produced the most shoots (14.33 and 14.89, respectively), whereas the MS medium containing 200 mg L^{-1} of Ag NPs produced the fewest shoots (4.55). According to studies, the uptake of NPs by plant cell, tissue, and organ cultures is intimately correlated with the uptake of moisture and nutrients from the medium (Lee *et al*., 2010; Lin *et al.*, 2009).

Table 1: Application of nanoparticles in different crops.

Sr. No.	Nanoparticle	Crop	Plant process	Reference
1.	Silicon dioxide	Tomato	Increased seed germination	(Siddique *et al*., 2014)
2.	Titanium oxide	Mung bean	Increased production	(Manjunatha *et al.,* 2019)
3.	Nano green	Rice	25% more yield	Bhan *et al.,* 2018)
4.	Gold nanoparticles	Lettuce, cucumber	Improved seed germination rate	(Barrena *et al.,* 2009 (Arora *et al.,* 2012) (Savithramma *et al.,* 2012) (Gopinath *et al.,* 2014)
5.	Silver nanoparticles	Maize, *Brassica juncea*	Plant growth profile	(Sharma, 2012) (Salama, 2012)
6.	Zinc oxide	Soybean, wheat	Rate of growth and development	(Prasad *et al*, 2012) (Sedghi *et al.,* 2013) (Ramesh *et al.,* 2014)
7.	Carbon nanotubes	Tomato, Bt-cotton	Enhanced germination rate	(Morla *et al.,* 2011)

Nano based seed priming. Priming is the process of treating seeds before planting, which involves traditional methods such as pre-soaking and coating. According to Bruce *et al.* (2007), seed priming results in a physiological change in seeds that facilitates rapid germination and enhances crop activity by increasing plant resistance against both abiotic and biotic stresses (Arnott *et al.,* 2021). When seeds are treated with nanoparticle (NP) solutions, this process is called "nano-priming" (Torre Roche *et al.,* 2020; Waqas *et al.,* 2019). Feizi *et al*. (2013) hypothesised that seeds soaked in nano-priming solutions containing Ag NPs for a limited duration of 24 hours generate OH^-radicals, which loosen the seed coat cell walls and endosperm to induce seed germination. Furthermore, the increased perforation of water and nutrients via the seed coat in nano-primed seeds enhances the growth rate and germination of seedlings, as noted by Hussain *et al*. (2016). The binding capacity of nano-primed seeds was found to be superior to hydro, vitamin, and polyethylene glycol (PEG)-primed seeds (Dutta 2018; Mahakam *et al*., 2017).

Sundaria *et al.* (2019) found that priming wheat seeds with varying concentrations of iron oxide nanoparticles (Fe_2O_3 NPs) led to improved germination potential and uniformity. Meanwhile, Chandrasekaran *et al*. (2020) discovered that priming seeds with carbon nanoparticles (CNPs) resulted in higher germination rates compared to the control seeds and that seed priming with gold nanoparticles (AuNPs) often enhanced water absorption in maize plants. Additionally, soaking sunflower (*Helianthus annuus*) seeds in nano silicon solutions with lower concentrations (0.2 and 0.4 mM) improved their germination. Abbasi Khalaki *et al.* (2021) have found that nano-priming is a more promising approach than traditional priming methods for achieving feasible agricultural yields. Chandrasekaran *et al.* (2020); Zhu *et al.* (2019); Maharramov *et al.* (2019) have reported that seed germination and seedling vigour are potentially induced in various crops through nano-priming. In sustainable agriculture, bio-priming of seeds with plant growth-promoting rhizomicrobes (PGPRMs) is an important approach, similar to nano-priming, as noted by Lutts *et al.* (2016); Mahmood *et al*. (2016). Pudake *et al*. (2019) have described Bio-Nano priming as a convergent field of applied technology that aims to take advantage of the combined benefits of nano- and bioagent application for enhancing crop cultivation.

Seed Quality. Nanoparticles have both positive and negative impacts on the germination process and quality of seeds. They can accelerate germination, enhance seedling strength, and improve overall seed quality, which encompasses characteristics such as seed lot purity, viability, health, mechanical damage, and seed vigour, a trait that is difficult to quantify (Perry, 1980). Recent studies show that nanoparticles have a positive effect on the germination, vigour, and quality of seeds in various crops. For instance, Shyla and Natarajan (2014) investigated the use of inorganic nanoparticles, including zinc oxide (ZnO), silver (Ag), and titanium dioxide (TiO_2), for enhancing seed quality in groundnut cv. VRI-2. Furthermore, Sangili *et al*. (2017) found that zinc oxide nanoparticles at a concentration of 125 ppm improved seed quality parameters and stimulated early seedling growth in spinach and green gram (*Vigna radiata*). (Xiang *et al.*, 2015) explored the impact of ZnO nanoparticles on the germination of Chinese cabbage seeds (*Brassica pekinensis* L.) and determined that treating the seeds with ZnO nanorods and zero-valent iron (ZVI) nanoparticles led to an improvement in the seeds' physiological and biochemical properties, resulting in increased vigour and viability. This finding is consistent with previous research conducted on black gram by Senthil Kumar (2011) and on tomato by Sridhar (2012).

Plant Growth Regulators (PGR). Nanomaterials (NMs) combined with plant growth regulators (PGRs) are primarily utilized for detecting small amounts of plant hormones in plants and for adjusting hormone levels to optimize production. Additionally, NMs aid in the absorption and transportation of PGRs into the plant. Chen *et al., (*2018) developed a novel magnetic sorbent, $Fe_3O_4@SiO_2/GO/\beta$-Cd, using β-Cyclodextrin modified magnetic graphene oxide material, for enriching and purifying PGRs in plants prior to GC-MS detection. Li *et al.* (2020) utilized crystalline porous polymer material to create a sorbent for detecting PGRs. To encapsulate the PGR GA-3, Santo Pereira *et al*. (2017) developed alginate/chitosan (ALG/CS) and chitosan/tripolyphosphate (CS/TPP) nanocarriers. Finally, Chakravarty *et al.* (2015) validated the effects of graphene quantum dots as enhanced PGRs on coriander and garlic growth.

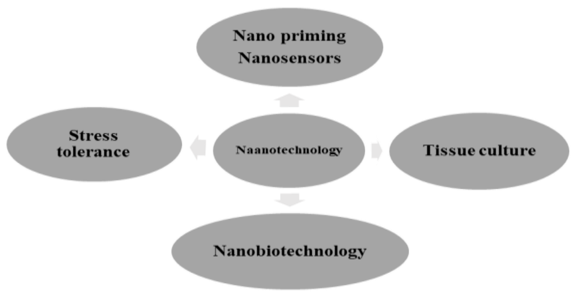

Fig. 1. Different applications of Nanotechnology.

Opportunities. The most amazing use of nanotechnology in the contemporary environment is "crop enhancement." Tissue culture, molecular breeding, genetic engineering, transgenic methods, and other fields offer a wide range of opportunities. Nanotechnology's entry into plant breeding has the potential to bring about enormous, abrupt changes that will immediately benefit the global economy. According to Prasad *et al.* (2017), biopolymer-derived nanomaterials (cellulose and starch) are safe for people and have grown in popularity all over the world since they are widely recognised as harmless and are not hazardous to people. These days, nanotechnology is an essential tool for addressing issues with agricultural and food security. Also, the expansion of nanotechnology in plant breeding can help us develop quick-thinking, future agricultural systems (Singh *et al.,*2020)

CONCLUSIONS

The application of nanotechnology in plant breeding holds great promise and has the potential to dramatically improve crop growth, output, and quality. Nano-derived devices (nano-sensors, nanoparticles) are widely used in plant breeding and genetic transformation of crops to develop improved varieties through appropriate breeding programs However, there are still obstacles to overcome in terms of producing safe and effective nanotechnology-based products for agriculture. Despite these challenges, the potential benefits of nanotechnology in plant breeding are too significant to ignore and deserve further investigation and advancement through additional research and development. The integration of nanotechnology in tissue culture has shown great potential for improving breeding strategies and enhancing crop productivity. Using various nanomaterials and nanotools, researchers have been able to develop more efficient methods for plant transformation, genome editing, and gene expression analysis. Using various nanomaterials and nanotools, researchers have been able to enhance seed germination rates, reduce the negative effects of environmental stressors, and improve overall plant growth and development.

FUTURE SCOPE

Nanotechnology has the potential to revolutionise the field of plant breeding and tissue culture by offering new tools and methods to manipulate plant cells and tissues at the nanoscale level. In plant breeding, nanotechnology can be used to develop novel plant varieties with enhanced traits such as increased yield, disease resistance, and nutrient efficiency. Nanoparticles can be used to deliver genetic material directly into plant cells, allowing for precise genetic modifications and accelerating the breeding process. In tissue culture, nanotechnology can be used to create artificial environments that mimic the natural conditions required for plant growth and development, enabling the production of large numbers of plants in a short period of time. Nanoparticles can also be used to deliver nutrients and growth regulators to plant cells, facilitating their growth and development. Overall, the future scope of nanotechnology in plant breeding and tissue culture is immense, and it has the potential to revolutionise the way we produce and cultivate plants.

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Conflict of Interest. None.

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