AgriCos e-Newsletter
ISSN: 2582-7049
AgriCos e-Newsletter
Open Access Multidisciplinary Monthly Online Magazine
Volume: 05 Issue: 10 October 2024 Article No: 10

Nanobionics and their Current State of Art in Sustainable Agriculture

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SUMMARY

Continuous rise in the accumulation of heavy metals due to anthropogenic activities imparts abiotic stresses like soil degradation, salinity and drought pose and thus pose a significant threat to the plants. Therefore, addressing the nutritional needs and demands of an everlasting population under such adverse conditions is crucial and challenging. Traditional methods for remediating the accumulation of heavy metals in contaminated soil are expensive, time-consuming and are unsustainable. Therefore, nanobionics offers a promising solution by enhancing the crop resilience, stress tolerance and can potentially increase the crop yields in a safe and sustainable way. This study highlights the nanobionics effects on plant physiological traits and growth and also discusses the numerous challenges associated with sustainability of the agricultural sector and the potential for future research.

INTRODUCTION

Sensitive plants must develop complex defense mechanisms against the severe environmental challenges particularly the abiotic stress like heavy metals (HM's) accumulations in soils, land degradation, droughts and salinity which are responsible for lowering the agricultural productivity. Addressing these issues is crucial and thus becomes essential for balanced food production for the growing global population (*Sharma A et al.,2022*). Implementation of traditional methods for improving plant resilience are limited and therefore leads to impart focus on innovative techniques like nanopriming. Nanopriming uses nanoparticles in order to enhance the seed germination, seedlings growth and imparting stress tolerance, which ultimately ensures the increase in crop yields and food quality. Numerous studies showed that the nanoparticles, such as silver, zinc oxide and silicon oxide have improved the germination rates and stress resistance in plants. Therefore, in recent advancement, nanobionics for mitigating the toxicity of HM's, drought and salinity and their further effects on plant physiological traits, growth indices and root architecture, while, considering the potential impacts of nanobionics on crops (*Shah T et al., 2021*).

Nanobionics and Physiological Traits

Nanomaterials (NM's) are incorporated into the plants to enhance natural processes such as photosynthesis and to introduce non-native functionalities like making plants into environmental sensors or light-emitting devices. Functionalized nanoparticles (FNP's) actively improves the photosynthesis process by localizing within plant tissues and organelles such as chloroplasts (active site for photosynthesis). For instance, single-walled carbon nanotubes (SWCNT's) can be introduced to chloroplasts for enhancing plant photosynthetic efficiency by increasing the rate of electrons transport. NP's must pass through the plant cell wall and membrane to enter into the cells and their design such as the use of chitosan coatings facilitates this process (*Sharma A et al.,2022*). SWCNT's absorbs visible near infrared light, generating excitons which enhances the photosynthesis of electrons flow. Nanopriming with SWCNT's has been shown to significantly increase the photosynthesis activities. Additionally, NP's can be engineered for specific targeting within plant cells such as using lipid exchange envelope penetration (LEEP) to facilitate nanoparticle entry into chloroplasts. This method has also been employed to develop the optoelectronic nanosensors for real-time monitoring of plant signaling molecules (*Amritha et al., 2021*). Furthermore, NM's can be used for genetic modification, where they deliver DNA to specific organelles like chloroplasts, enhancing the plant performance and offering new functionalities for agricultural applications including environmental sensing.

Nanobionics and growth indices

Nanoparticles (NP's) not only promotes the plant growth but also protect the plants from various abiotic stresses. Due to their large surface area and small size, NP's can bind onto toxic metals like zinc, iron and cobalt, and thus, reducing their availability and also mitigating their harmful effects. NP's small enough to pass through cell wall pores and can reach into plasma membrane, and therefore, interactions with NP's may even enlarge these pores enhancing their uptake. Studies have shown that plants respond defensively to abiotic stress when exposed to NP's. For instance, SiO2 NP's improves the transpiration rates, water-use efficiency total chlorophyll content and carbonic anhydrase activity in *Cucurbita pepo* under salt stress (*Shah T et al., 2021*). Titanium dioxide (TiO2) NP's can alter the electron transport chain in chloroplasts, affecting oxygen evolution and slowing down the photo-reduction activity. The interaction and absorption of NP's leads to molecular changes that influence the plant morphology and physiology. NP's also aids in seed preparation, facilitating water absorption by penetrating tough seed coats which enhances growth and viability. Specific crops like *Zea mays*, *Brassica juncea*, and *Glycine max* have shown improved growth when exposed to multi-walled carbon nanotubes (MWCNT's), with these NP's accumulating within the endosperm. Additionally, mesoporous silica NP's (MSNs) do not induced stress even at high concentrations and thus, making them a safe option for delivery system. Other NP's, like those made from copper and zinc have also shown positive impact on seed germination in *Vigna mungo* (*Amritha et al., 2021*).

Nanobionics and root architecture

Root exudates secreted by plant roots can be a significant barrier to effective nanoparticle uptake. These exudates include both high molecular weight (MW) substances like mucilage and proteins and low MW substances such as organic acids, amino acids and sugars. Approximately 30-40 per cent of photosynthetically fixed carbon is released as root exudates, which helps the plants to sense soil conditions and respond by releasing specific organic compounds, such as oxalates and malates especially under nutrient deficient conditions (*Jat SK et al., 2020*). Root exudates can affect NP absorption by influencing their size and charge, as seen with nano-Cu(OH)2 and nano-MoO3, which increased in size and nano-CeO2 and nano-Mn3O4 which decreased. Additionally, root exudates like citric acid can enhance NP dissolution and uptake, as observed in studies involving cerium oxide NP's. Other barriers to NP uptake include the root epidermis, apoplastic and symplastic pathways and the Casparian strip which can all impact the movement of NP's through root tissues (*Kumar S et al., 2019*).

Nanobionics and stress tolerance

Different organelles have unique mechanisms for nanoparticle (NP) movement across membranes. For instance, ZnO NP's have been shown to induce the programmed cell death in tobacco BY2 cells by causing oxidative stress and dysfunction in the endoplasmic reticulum and mitochondria. Excessive reactive oxygen species (ROS) accumulation and oxidative damage are common in the stressed plants. To balance ROS production and scavenging, scientists are exploring the use of NP's to enhance ROS homeostasis, thereby supporting stress tolerance and nano-efficient agriculture. NP's can improve photosynthesis of stressed plants by promoting root growth, regulating water metabolism, maintaining ionic balance and activating antioxidants defense. However, carbon nanomaterials (CNM's) can harm the plants if not carefully managed. NP's also enhanced seed germination, growth and yield by boosting various physiological processes and antioxidant activities (*Kumar S et al., 2019*). Additionally, they can act as artificial antennas for chloroplast for aiding absorption. Nanobionics in agriculture is advancing with the use of nanofertilizers and nano-pesticides offers a sustainable alternative to traditional bio-remediation techinques.

Nanobionics and photosynthesis modulation

Modulating photosynthesis is a key strategy to significantly boosting the crop production levels and recent research suggested its feasibility. C4 plants generally exhibits better photosynthetic efficiency than C3 plants, which make up 85 per cent of the ecosystem's flora. Traditional methods to enhance photosynthesis include improving RuBisCO efficiency, converting C3 plants to C4 photosynthesis and optimizing the chlorophyll absorption (*Turgut-Kara N et al., 2020*). Nanoparticles (NP's) like TiO2 have emerged as effective nanobionics for enhancing photosynthesis by improving the light absorption and protecting chloroplasts from photochemical stress. TiO2 as NP's also boost RuBisCO efficiency and chlorophyll content in plants like *Brassica napus*. Other metal based NP's, such as Au, ZnO and Ag improves photosynthesis by increasing the chlorophyll content, electron transport rates and photosystem function. However, NP effectiveness is dose-dependent with excessive concentrations potentially damaging photosynthetic processes. For instance, Ag as NP's enhances the chlorophyll content at specific doses but can reduce if it is provided at higher levels.

Major Concern and Future Prospects

The use of nanoparticles (NP's) in agriculture holds great promise with engineered and green-synthesized explored for enhancing crop production. Nanobionics boosts the photosynthesis and nutrient-use efficiency (NUE) and also offers great potential in stress tolerance, target based agrochemical delivery and precision farming. Over 9400 nano-based product exist, out of which 229 majorly focused on agriculture. However, key issues must be addressed including application guidelines, crop-specific dosages, environmental impact and toxicity in food chains. Accumulation of metal-based NP;s in soil could harm the beneficial microorganisms and ecosystems and ultimately pose risks to crop growth and quality(*Kumar S et al., 2019*). Sustainable development requires balanced agricultural advancements with environmental protection and human health, ensuring safe and cost-effective NP's applications for future farming.

CONCLUSION

Nanobionics can enhance the photosynthesis by boosting like absorption, increasing thylakoids and chlorophyll content and thus leading to improved biomass and crop yield. Nanocarriers that responds to stimuli like pH or temperature enable controlled agrochemical release, optimizing nutrient-use efficiency and reducing wastes. These approaches promotes cost-effective, sustainable agriculture are crucial for achieving the UN SDG "Zero Hunger" goal by 2030. However, increasing NP's use in agriculture poses risks as their accumulation in soil may harm plant health, reduce crop yields and affects soil fertility. Additionally, NP's can bioaccumulate causing oxidative stress, DNA damage, and apoptosis in aquatic and terrestrial organisms.

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