Nanotechnology in quinoa production

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Quinoa (*Chenopodium quinoa* Willd.) is a significant crop that was cultivated by ancient societies in the Andean region of South America. It is an annual plant with broad leaves and starchy seeds and it exhibits characteristics of a halophyte, meaning it can tolerate conditions like drought and salt stress, which are common in the Mediterranean area. Quinoa is not technically a cereal but falls under the category of pseudo-cereals. It has gained recognition for its exceptional nutritional value and is often referred to as "the mother grain."One of the notable features of quinoa is its high protein content, which makes it a suitable substitute for dairy proteins. The seeds of quinoa are considered nutritionally superior and contain polyunsaturated fatty acids (PUFAs) that have positive effects on insulin sensitivity and cardiovascular health. Quinoa also provides a well-balanced distribution of essential amino acids, fatty acids, minerals, vitamins, dietary fibers, and carbohydrates. In addition to its nutritional value, quinoa exhibits resilience in challenging environmental conditions. It can thrive in cold, salty and drought-prone areas, earning it the nickname of the "golden grain." As a result, quinoa has recently been recognised as a key model crop for studying how plants react to salt and water stress. This is so that it can adapt to various environmental circumstances as a stress-tolerant plant. Moreover, quinoa's high salt tolerance traits have drawn the attention of experts. The processes by which quinoa plants tolerate various saline levels at different stages of growth have been the subject of several investigations.

Quinoa was chosen as a protein crop for organic feed in Denmark and was also suggested for those who have celiac disease. The quinoa market is now expanding quickly on a worldwide scale because of its exceptional nutritional qualities. There are now nine registered cultivars in Europe, including Denmark has contributed three quinoa varieties, namely Titicaca, Puno, and Vikinga. Additionally, in Denmark, there are three varieties of quinoa known as Titicaca, Puno, and Vikinga. Additionally, Denmark cultivates three other quinoa varieties, including Atlas, Pasto, Riobamba, and Red Carina. Furthermore, France grows a variety called Jessie. With the use of several methods and technologies, the agricultural industry may gain a lot from the applications of contemporary biological research. However, use of emerging technology *i.e.* nanotechnology can gain the importance in quinoa production.

The study of materials at length scales less than 100 nm is referred to as nanotechnology. Nanotechnology, which involves working with materials at the scale of one billionth of a meter (nano), has the potential to enhance agricultural productivity through genetically improved plants, targeted delivery of genes and medications at the cellular level, and nano-array-based gene technologies for stress-tolerant plant and animal expressions. These advancements in nanotechnology not only hold promise for increasing agricultural output but also offer benefits to consumers, producers, farmers, ecosystems, and society as a whole. As a result, future developments in nanotechnology are expected to be the primary catalysts for long-term economic growth in this field.

According to available reports, nanomaterials have shown promising effects in enhancing plants' resistance to salt stress. Studies on nanoparticles (NPs) have indicated that their concentration-dependent actions can aid plants in overcoming abiotic stress. For instance, nano zinc particles have been successfully utilized to mitigate the adverse impacts of salinity in irrigation water on cotton plants. These nano-Zn particles have effectively reduced the P/Zn ratio in cotton leaves, leading to improved resistance to salinity.

Silver nanoparticles (Ag NPs) are widely produced for industrial purposes and offer beneficial attributes like antibacterial properties and a high electrochemical reduction potential. Therefore, understanding the appropriate concentrations of Ag NPs is crucial for assessing their impact on plant growth, physiology, and stress tolerance under different environmental conditions. The combination of biotechnology (plant tissue culture) and nanotechnology (silver nanoparticles) presents an intriguing avenue for investigating the physiological responses of a plant, such as quinoa, when subjected to induced stress. Surprisingly, there is a dearth of documented research on the effects of Ag NPs on in vitro-grown quinoa under induced salt stress in existing scholarly literature. Thus, exploring this area of study could provide valuable insights into how Ag NPs may influence plant responses to abiotic stimuli

REQUIREMENT OF NANOPARTICLES

Compared to bulk substance, nanoparticles offer better characteristics.

- NPs can be layered on surfaces, resulting in a greater surface area and increased activity.
- May change a material's strength or electrical properties, increasing their chemical reactivity.
- The properties of materials at the nanoscale exhibit distinct physical, chemical, and biological attributes compared to their counterparts at the molecular or bulk level.
- NPs show improved membrane permeation through biological barriers.
- NPs contain antibacterial properties and respond to the targeted species specifically.
- Electrostatically interact with the membrane and attach, compromising the membrane's integrity.
- Ultra-Hard: less likely to have flaws.

Nanotechnology addresses some of the biggest issues facing agriculture:

1) **Food security for an expanding population:** When employed in the realm of food packaging, nanomaterials offer numerous benefits, such as enhanced mechanical barriers, improved detection of microbial contamination, and potentially increased absorption of nutrients. This application represents one of the most prevalent uses of nanotechnology in the food industry and related sectors.
2) **Poor agricultural productivity:** Producing meals of exceptional quality in greatly better practical forms and increasing nutritional bioavailability are both possible thanks to nanotechnology. Numerous studies are concentrating on expanding the use of nanotechnology for agricultural production and food processing.
3) **A lower input efficiency for agriculture:** Incorporating micronutrients in nano form or encapsulated in nanoparticles can result in a controlled and gradual release of nutrients, leading to enhanced plant growth, increased agricultural productivity, improved soil health, and accelerated nutrient absorption by plants. For example, the application of nano zinc oxide in small quantities to zinc-depleted soil has been shown to promote plant growth and stimulate various physiological responses, including elongation of shoots and roots, greater fresh and dry weight of plants, and improved photosynthesis.
4) **Non-sustainable agriculture operations:** The adoption of behaviours that will ultimately result in the deterioration of the soil, land, and other natural resources required for farming and a healthy future.
5) **Vast inaccessible places:** The Global Land Assessment of Degradation estimates that since the 1950s, almost two billion hectares of land have been lost to degradation

globally. These two billion hectares make up 22% of all the farmland, pastures, forests, and woods in the globe.

6) **Product waste:** Products packaging, yard debris, clothing, food scraps, appliances, paints and batteries are among the things that are frequently included in this category. The majority of the stuff that towns gather are dumped in landfills all around the world.
7) **Perishability/short shelf life:** Foods that spoil quickly after being harvested or produced include fruits and vegetables, dairy, seafood, and meat products. The time it takes for them to stop being marketable or edible varies on the food product in question as well as a number of external variables.
8) **Diseases and climate change vulnerabilities as a result of global warming:** These disturbances have adverse effects on human health across multiple dimensions. They contribute to the rise of respiratory and cardiovascular diseases, injuries, and premature deaths resulting from extreme weather events. They also lead to changes in the occurrence and geographic spread of food- and water-related illnesses, as well as other infectious diseases. Furthermore, these disruptions pose risks to individuals' mental well-being.

Scientists are actively exploring novel applications of nanotechnology in the field of seed business. It is anticipated that in the coming years, substantial advancements will be made in the agricultural and seed industries as a result of these efforts.

NANOTECHNOLOGY USES IN AGRICULTURE

In addition to improving the safety of food supplies for the protection of consumers and producers, nanotechnology has the potential to introduce new functionality (value-added products) for food, fibre, and agricultural commodities. It can also increase the efficiency and quality of agricultural production and food storage. To transform agricultural practices, mitigate or eliminate the environmental impact of conventional farming and enhance crop quality and yield, the development of a sophisticated agricultural system utilizing smart nanotools has been proposed (Sekhon, 2014; Liu and Lal, 2015). This approach holds the potential to revolutionize farming methods and pave the way for sustainable and efficient agricultural practices in the future.

Nanotechnology has a significant presence in and plays a vital role in advancing biosensor development, making it an ideal field to leverage its unique characteristics. The incorporation of nanomaterials can greatly enhance the sensitivity and performance of biosensors in various applications (Fraceto *et al*., 2016). Additionally, novel signal transduction technologies have emerged, expanding the possibilities for biosensor implementation (Sertova, 2015). Furthermore, the use of nanomaterials has enabled the miniaturization of numerous (bio)sensors, leading to the creation of tiny, intelligent devices such as nanosensors and other nanosystems. These advancements are pivotal in biochemical analysis (Viswanathan and Radecki, 2008; Sertova, 2015; Fraceto *et al*., 2016). Moreover, nanotechnology facilitates the rapid detection of mycotoxins present in various food items (Sertova, 2015). These developments showcase the vast potential of nanotechnology in revolutionizing biosensor technology and its applications in diverse fields, including food safety and biochemical analysis.

Indeed, nanotechnology has found numerous applications in agriculture, and some of the key areas include:

(1) Nano formulations of agrochemicals: Nanotechnology allows the development of nano-sized formulations of pesticides and fertilizers, enabling targeted and controlled delivery to crops, leading to improved crop protection and enhanced nutrient uptake.

(2) Nano sensors in crop protection: Nano sensors are utilized to detect and monitor diseases in crops, as well as residues of agrochemicals, facilitating timely interventions and reducing the risk of chemical exposure.

(3) Nanodevices for plant genetic engineering: Nanotechnology plays a role in developing nanodevices for precise and efficient genetic engineering of plants, enabling the introduction of desirable traits and genetic modifications.

(4) Plant disease diagnostics: Nanotechnology-based diagnostic tools help in early detection and identification of plant diseases, allowing for rapid response and better disease management.

(5) Animal health, breeding, and poultry production: Nanotechnology applications extend to animal health, supporting advanced breeding techniques and enhancing poultry production through improved feed formulations and disease management.

(6) Postharvest management: Nanotechnology assists in developing innovative solutions for postharvest management, such as nano-coatings for extending shelf life, reducing spoilage, and maintaining the quality of harvested crops.

These applications showcase the potential of nanotechnology to revolutionize agriculture and contribute to sustainable, efficient, and environmentally friendly farming practices.

Indeed, the potential benefits of nanotechnology in agriculture, food production, fisheries and aquaculture are significant, but they must be carefully evaluated in light of various considerations. Experts emphasize the need to balance the advantages of nanotechnology with potential concerns related to land, water and environmental impacts, as well as occupational safety for workers involved in these industries. Currently, there are ongoing investigations, testing and in some instances, practical applications of nanotechnology in the field of food technology. The use of nanotechnology holds promise for improving various aspects of food production, storage and safety. However, it is crucial to conduct thorough research and assessments to ensure that the implementation of nanotechnology in the food sector is safe and environmentally responsible. By carefully weighing the potential benefits against possible risks, stakeholders can make informed decisions and develop responsible practices to harness the full potential of nanotechnology in agriculture and food-related industries. Striking the right balance will lead to sustainable and innovative solutions that can help address challenges in food production, resource management and food security.

Agriculture and food technology are now testing nanotechnology uses. The use of nanoparticles in agriculture aims to boost plant yields and decrease the need for plant protection product spraying. Nanotechnology usage for illness diagnosis and therapy include nanoparticles and nano capsules, for example. Moreover, gadgets generated from nanotechnology are being investigated in the fields of plant breeding and genetic modification. Absolutely, nanotechnology has the potential to revolutionize all stages of agricultural product production, processing, storage, packaging, and transportation. By applying nanotechnology, various aspects of the agricultural and food industries can be significantly improved and transformed.

In farming methods, nanotechnology can lead to the development of nano formulations of agrochemicals, which enable precise and targeted delivery of pesticides and fertilizers to crops, resulting in better crop protection and increased yields. Nanotechnology can also facilitate controlled and slow release of nutrients to enhance plant nutrition and growth. In disease detection, nano sensors and nanodevices can be used to rapidly identify and monitor diseases in crops and livestock, allowing for early detection and effective disease management. Similarly, nanotechnology-based diagnostic tools can aid in the quick and accurate detection of foodborne pathogens and contaminants, ensuring food safety. In pest management, nanotechnology offers innovative solutions, such as nano-encapsulation of biopesticides and targeted delivery systems, which can minimize the environmental impact of pesticides and improve their efficacy in controlling pests.

Moreover, nanotechnology can contribute to the development of smart packaging materials that can monitor food freshness, detect spoilage, and extend shelf life, leading to reduced food waste and improved food quality. Although there is lot of promise for nanotechnology in agriculture, several concerns need to be resolved as part of the risk assessment. In this regard, several biopolymers, such proteins and carbohydrates, are used as nanoparticle attractants because of their low impact on the environment and human health.

NANOTECHNOLOGY IN SEED SCIENCE

It makes sense to develop solutions for rain fed agriculture because more than 60% of the net area cultivated in India is rain fed. The germination of rain-fed crops is now being improved by a team of researchers using carbon nanotubes and metal oxide nanoparticles. By greater moisture permeability, carbon nanotubes have been shown to improve tomato seed germination by Khodakovskaya *et al*. (2009). According to their research, carbon nanotubes (CNTs) penetrate the seed coat to act as new pores for water permeation and as a route for water to go from the substrate into the seeds. These procedures promote germination, which the rainfed agricultural system may use.

NANOTECHNOLOGY IN SEED HEALTH MANAGEMENT

Nano-coatings composed of various metals such as Zn, Mn, Au and Ag, among others, have shown promising potential in protecting seeds against infections and enhancing crop performance. By incorporating nano particles and encapsulating specific bio-agents, these coatings can effectively control both seed-borne and soil-borne diseases. The use of nano-coatings on seeds offers several advantages. Firstly, it reduces the need for excessive seed application, leading to minimized seed rates while maintaining optimal field stand. This ensures efficient seed utilization and cost-effectiveness for farmers. Secondly, the controlled release of bio-agents from the nano-coatings aids in preventing infections and diseases that could otherwise harm the seeds during germination and early growth stages. By safeguarding seeds against infections, the nano-coatings contribute to healthier and more vigorous seedlings, leading to increased crop performance and yield potential. Additionally, the protection provided by these coatings can lead to more resilient and productive crops, contributing to food security and sustainable agriculture.

Research and development in this area continue to explore the possibilities of nano-coatings and their effectiveness in enhancing seed quality, reducing disease pressure and improving overall agricultural productivity. As this technology advances, it has the potential to revolutionize seed protection and contribute to the development of more sustainable and efficient agricultural practices. To handle infestations effectively, seeds can be applied to nano cores that have been coated with pesticides. These nano cores may be modified to become "gut busters," programmable products that only release pesticides in alkaline conditions like an insect's stomach.

NANO-ENHANCED SEED CONDITIONING

By carefully rehydrating seeds, a process known as seed priming induces pre-germinative metabolism, which boosts germination rates and vigour (Paparella *et al*., 2015). Even in the face of abiotic difficulties like salt, dryness, excessively high and low temperatures, etc., seed priming is a physiological strategy that benefits by increasing seed germination. Priming is viewed as a stress exposure that occurs before to germination and creates a memory of that stress as well as information that will improve the physiological processes of the plant. Abiotic stresses that influence agricultural plants can be managed through priming, also known as seed pre-conditioning.

Bourhim *et al*. (2022) experimented pre-germinative treatments on three genotypes of quinoa for improved seed germination in high saline conditions to test the priming impact on the enhancement of seed germination using filter paper in petri dishes utilising the seeds of three quinoa genotypes: Puno, Titicaca, and Q5. Concluding the study, it retained that quinoa genotypes had ability to germinate under conditions of high salt varied; among the three, the Puno variety was the most resistant to 300 and 400 mM NaCl, followed by ICBA-Q5 and Titicaca. Under salt levels of 300 and 400 mM NaCl, the priming treatment, which involves soaking seeds for 8 hours in a solution of zinc sulphate at a concentration of 1 g/L, is effective in increasing the germination percentage by more than 100%. For the quinoa genotypes that were investigated, the germination threshold was thought to be 400 mM NaCl.

Nano-priming is a cutting-edge seed priming technique that aids in boosting seed germination, seed development, and yield by offering plants resistance to various conditions.

Nano-priming is substantially more effective than all other seed priming strategies. The development of increased surface responsiveness and electron exchange capabilities connected to various parts of plant cells and tissues are two of nanoparticles' (NPs) significant properties in seed priming. Effects of nano-priming include activating ROS/antioxidant processes in the seeds, generating hydroxyl radicals to weaken cell walls, serving as an inducer for the rapid hydrolysis of starch, and inducing the formation of nanopores in the shoot that help in the absorption of water. Additionally, it promotes the expression of aquaporin genes, which function in the water consumption promotes the propagation of ROS, or H_2O_2, across cellular membranes. In the context of nano-priming, which involves using nanoparticles (NPs) smaller than 100 nm, "priming" describes the process of constructing a stress threshold by gradual, moderate stress. Additionally, this may be one of the best methods for addressing dormancy difficulties and enhancing seed germination in forest species (upland boreal), indicating that nano-priming may be useful for attempts to restore forests.

NANOTECHNOLOGY AND INVITRO CULTURE IN MITIGATION OF SALINITY STRESS

Quinoa is a versatile crop that is primarily produced for its rich historical, ecological, and nutritional history. The plant may be cultivated in locations with marginal soils that receive little rainfall since it is well suited to many settings. In the 1970s of the previous century, this crop's significance and unique qualities started to emerge. So, it is necessary to use innovative technologies to boost this crop's yield under salinity-related situations. By utilising many elements, including nanoparticles and others, the plant tissue culture can play a significant role in providing the necessary circumstances to examine the plant responses to salt stress. Stress caused by salt has a deleterious influence on a number of biochemical and physiological processes involved in plant growth and productivity. Lowered soil osmotic potential, nutritional instability, increased ionic toxicity (salt stress), or combinations of one or more of these factors are some frequent impacts of salinity stress on plants.

Kalteh *et al.* 2014. In this study, morphological features (shoot fresh weight and dry weight) and physiological variables (leaf chlorophyll and proline concentration) were examined in basil. The effects of the salt stress on growth and development parameters were considerable. By increasing the quantity of NaCl, leaf dry and fresh weight decreased, but it considerably (P0.01) rose when silicon nanoparticles were used. Chlorophyll content decreased under salt stress, but it rose after being treated with silicon nanoparticles. As a reaction to stress, proline content rose under salt stress. Additionally, silicon nanoparticles caused proline to rise, which was brought on by the plant's induction of tolerance. Application of silicon nanoparticles lessened the pollution impacts caused by basil's saltiness. Regarding salt levels, plant types, and environmental factors, this investigation found that using silica nanoparticles (S3) was the optimum therapy for promoting plant development.

NANOTECHNOLOGY POTENTIAL IN SEED PRIMING FOR SUSTAINABILITY IN AGRICULTURE

Khodakovsky *et al*. (2009) examined to enhance the germination of rain-fed crops, a team of researchers is now experimenting with carbon nanotubes and metal oxide nanoparticles. Nanotechnology can contribute to the sustainability of agriculture. Seed nano-priming is an efficient process that can change seed metabolism and signalling pathways, affecting not only germination and seedling establishment but also the entire plant lifecycle. various benefits of using seed nano-priming, such as improved plant growth and development, increased productivity and a better nutritional quality of food. Nano-priming modulates biochemical pathways and the balance between reactive oxygen species and plant growth hormones, resulting in the promotion of stress and diseases resistance outcoming in the reduction of pesticides and fertilizers.

Nanotechnology has the potential to contribute to the sustainability of agriculture, and seed nano-priming is one such application. Seed nano-priming involves treating seeds with nanomaterials to enhance their performance and overall plant life cycle. One of the advantages of seed nano-priming is its impact on seed metabolism and signalling pathways. By altering these processes, nano-priming can influence germination, seedling establishment, and subsequent plant growth and development. This can lead to improved plant growth, increased productivity and even enhance the nutritional quality of the food produced.

Additionally, seed nano-priming can modulate biochemical pathways within the plant, as well as the balance between reactive oxygen species (ROS) and plant growth hormones. This modulation can result in enhanced stress resistance and disease resistance in plants. As a result, the use of nano-priming can reduce the reliance on pesticides and fertilizers, leading to more sustainable agricultural practices. It's worth noting that the specific mechanisms and effects of seed nano-priming may vary depending on the type of nanomaterial used, concentration, and the plant species involved. The field of nanotechnology in agriculture is still developing, and more research is needed to fully understand its potential and ensure its safe and responsible use.

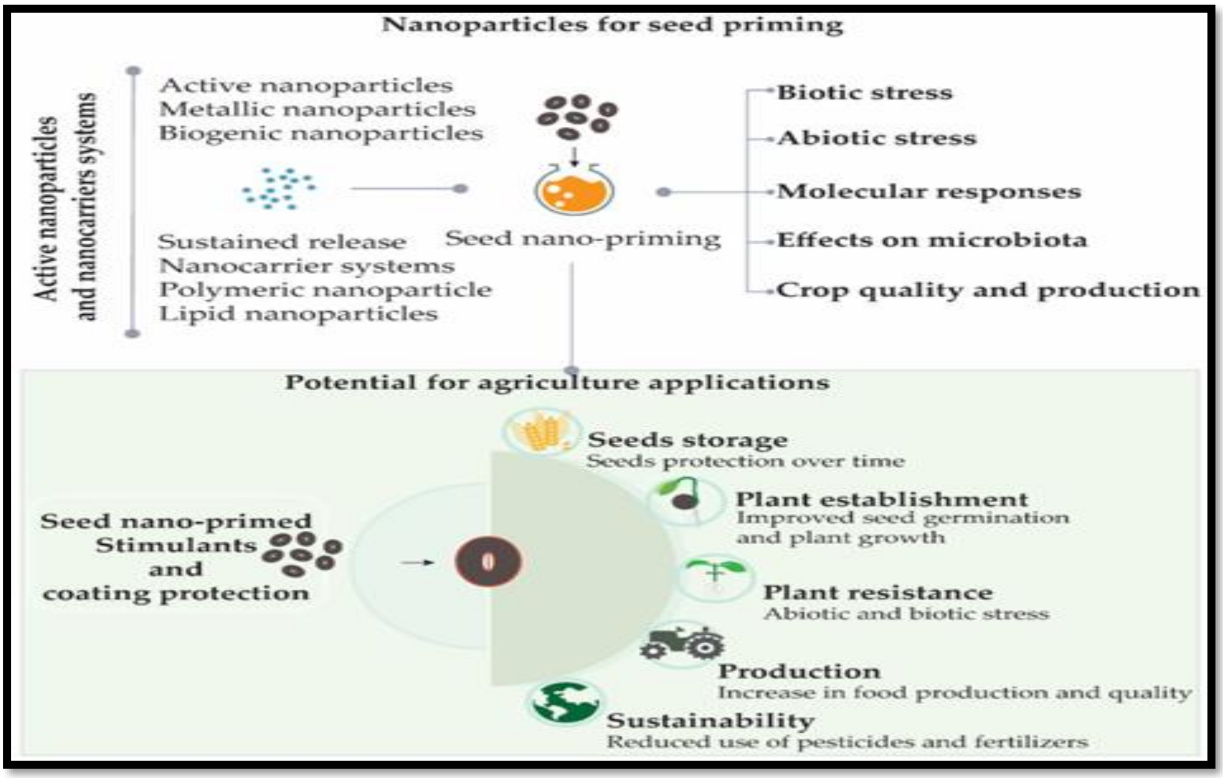

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Fig. 1. The potential applications of seed nano-priming in agriculture

In Fig.1, the subjects of seed nano-priming and its potential advantages for sustainable agriculture are explored in this study. The application of seed nano-priming can increase plant establishment in the soil and minimise the demand for fertilisers in addition to protecting seeds during storage. Plants that are developing more quickly are better able to compete for resources with weeds, which raises production and food quality. Pesticide use may decrease as a result of the plants' increased resilience to biotic and abiotic stressors.

EFFECT OF SEED PRIMING WITH ZnO NANOPARTICLES

The application of zinc oxide (ZnO) nanoparticles on wheat using various methods, such as foliar spray, soil mixing and seed priming, has been studied. When ZnO nanoparticles are applied at low concentrations, they have been found to promote the production of antioxidant enzymic and non-enzymic molecules, phytohormones and overexpression of new water channels. These effects can improve the absorption of water and nutrients, benefiting the initial growth of seedlings when ZnO nanoparticles are used for seed priming.

It is important to note that the specific concentrations, exposure durations, and experimental conditions may vary across different studies. Further research is still needed to fully understand the mechanisms behind the effects of ZnO nanoparticles on plant physiology and to ensure the safe and effective use of nanomaterials in agricultural practices.

Saponin priming improves quinoa's resilience to saline conditions

10%, 15%, and 25% concentration saponin solutions were discovered to be the most efficient priming techniques for reducing the negative effects of salt stress during seed germination. These primed seeds' performances were subsequently assessed in pot research. Plants were watered with salty water that contained either 0 or 400 mM NaCl when they had six leaves. However, quinoa's growth, physiology, and yield were all considerably reduced by saline irrigation, but saponin priming was effective in reducing the impacts of salt stress Low ABA concentrations were linked to enhanced growth, physiology, and yield performance, superior plant water and gas relations (leaf photosynthetic rate, stomatal conductance), low Na+, and high K+ levels in leaves. Whereas, saponin priming may be utilised as a Simple and affordable solution for maintaining quinoa crop development in soils impacted by salt.

USING NANOTECHNOLOGY IN FERTILISERS AND PESTICIDES

Nanomaterials used as fertilizers in agriculture offer several features that can benefit crop growth and reduce environmental toxicity. Some of these features include:

1. **Improved crop quality:** Nanofertilizers can enhance nutrient uptake and utilization by plants, leading to improved crop quality in terms of yield, nutritional content, and overall health.

2. **Reduced environmental toxicity:** Nanofertilizers can be engineered to release nutrients gradually, reducing the risk of nutrient leaching and minimizing their impact on the surrounding environment.

Regarding the use of pesticides in the form of nanoparticles or nano-encapsulated pesticides by companies like Monsanto, Syngenta, and BASF, this technology has the potential to provide several advantages:

1. **Enhanced absorption:** Nanoparticle-based pesticides may be more readily absorbed by seedlings, leading to more effective pest control.

2. **Controlled release:** Nonencapsulated pesticides can be designed to release the active ingredients at specific times or under certain conditions, increasing their efficiency and reducing the need for frequent applications.

However, the use of nanoparticles in agriculture also raises concerns about their potential bioaccumulation in the food chain. Plants can serve as essential pathways for the transfer of nanoparticles into the food web.

It is important to note that the use of nanoparticles in agriculture is still an evolving field and researchers are continuously studying their potential benefits and risks. The safe and responsible use of nanomaterials in agriculture requires thorough understanding and assessment of their effects on crops, the environment and human health. As with any new technology, careful regulation and monitoring are essential to ensure its sustainability and minimize any potential negative impacts. When tryptophan is converted to auxin or indoleacetic acid (IAA), as well as throughout the metabolic processes necessary for the production of carbohydrates and chlorophyll, zinc plays a crucial role. Zn deficiency may have an impact on agricultural output and produce quality. For agricultural and public health, the emergence of pesticide resistance in pest insects has become a growing issue.

Magnesium oxide (MgO) is an important inorganic substance with a wide range of applications, including its use in adsorbents, fire retardants, ceramics, hazardous waste remediation and photoelectronic devices. As a result, various methods and strategies for synthesizing magnesium oxide nanoparticles (MgONPs) have been documented. One approach to produce MgONPs is through green synthesis techniques using non-toxic materials. For example, Ghidan *et al.* (2018) utilized non-toxic citrus limon leaf extract, acacia gum, and neem leaf extract to synthesize magnesium hydroxide (MgOH) nanoparticles.

In their study, Ghidan *et al.* 2017, examined the effects of different concentrations of MgONPs on the green peach aphid (GPA) in a greenhouse environment. Additionally, aqueous extracts of Punica granatum peels, Olea europaea leaves, and Chamaemelum nobile flowers were used to synthesize copper oxide (CuO), zinc oxide (ZnO), MgOH and MgO as nanomaterials.The synthesis of various nanomaterials, including copper oxide nanoparticles (CuONPs), zinc oxide nanoparticles (ZnONPs), MgOH nanoparticles (MgOHNPs) and MgONPs, can be achieved through a combination of physical and chemical techniques. However, the biosynthesis of nanoparticles using plant-based materials has gained increasing interest due to the need to reduce the use of environmentally hazardous compounds such as pesticides. Plants have shown the ability to reduce metal ions and participate in the synthesis of nanoparticles at a faster rate compared to microbes. This has led to the exploration of plant-mediated synthesis as a promising approach in the field of nanotechnology and biotechnology. Plant-mediated synthesis offers potential advantages in terms of scalability, sustainability and reduced environmental impact.

Nanotechnology has the potential to revolutionize seed packaging and handling by introducing innovative materials and technologies. Here are some examples of how nanotechnology can be applied in this field:

1. **Cellulosic nanocrystals:** Cellulosic nanocrystals can be incorporated into polymeric matrices to create nanocomposites, offering lightweight reinforcement for packaging materials. These nanocomposites can provide enhanced durability and cost-effectiveness, making them suitable for seed packaging applications.
2. **Ligno-cellulosic nanomaterials:** Ligno-cellulosic nanomaterials open up new possibilities for the development of novel and value-added biomaterials. These materials can be utilized in seed packaging to enhance properties such as mechanical strength, moisture resistance, and barrier properties.
3. **Nano sensors for seed storage:** Electronic noses (E-noses) equipped with nano sensors can detect and analyse gases released by seeds during storage. By monitoring the gas emissions, it is possible to assess seed quality and detect signs of deterioration. This enables the identification and removal of deteriorating seeds, ensuring only viable ones are used for planting.
4. **Nano polymer coatings:** Seeds can be coated with moisture-sensitive nano polymer membranes that respond to the presence of water. This coating allows germination to occur only when a specific moisture level (e.g. 45-50%) is reached. Such coatings help regulate and optimize germination conditions, enhancing seed viability and overall performance.
5. **Edible films with nanoparticles:** Edible films made from quinoa protein and starch nanoparticles can be developed for seed coating applications. These films can incorporate natural antioxidant compounds from plant sources (e.g. pomegranate peels) to provide protection against oxidative damage. The mechanical properties, permeability,

particle size distribution and other characteristics of these films can be optimized to ensure efficient seed coating and protection.

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