



Nanotechnology in Agriculture: A New Approach to Climate-Resilient Crops and Efficient Fertilizer Use

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Agriculture is facing several challenges, including climate change, water scarcity and the increasing cost of fertilizers. Drought, high temperatures and soil salinity can affect crop growth and reduce yields. At the same time, a considerable amount of applied fertilizer may be lost before plants can use it. Nanotechnology is attracting attention as a possible way to address some of these problems. Nano-fertilizers, nano-sensors and other nano-based products are being studied for their potential to improve nutrient supply, support plant growth under stress and reduce unnecessary input losses. Research has shown encouraging results in different crops, although the benefits vary with the material used, its concentration and the growing conditions. This article discusses how nanotechnology may contribute to climate-resilient agriculture and more efficient fertilizer management, along with the challenges that need to be addressed before its wider use.

Keywords: Nanotechnology, nanofertilizers, climate change, abiotic stress, nutrient-use efficiency

Introduction

Agriculture must produce more food, but with changing weather conditions and finite natural resources. Farmers are already facing irregular rainfall, long dry spells, rising temperatures and deteriorating soil quality. These conditions may influence crop growth, nutrient availability and the final yield. Fertilisers are important in meeting the nutrient requirements of crops but their application does not always lead to efficient use of nutrients. Nitrogen can be lost via volatilisation, leaching and denitrification. Phosphorus can be fixed in the soil. Such losses add to the cost of cultivation, and can also have environmental consequences.

In this situation, nanotechnology offers a new approach to crop and nutrient management. It involves the use of materials generally ranging from 1 to 100 nanometres in size. Because of their small size and distinctive properties, some of these materials can be used to develop new fertilizer formulations, plant treatments and agricultural sensors.

Nanotechnology for Climate-Resilient Crops

Drought Stress: Water shortage affects almost every stage of crop growth. Under drought conditions, plants may show reduced leaf expansion, lower photosynthetic activity and poor nutrient uptake. Severe water stress can also increase the production of reactive oxygen species (ROS), which may damage plant cells. Researchers are exploring silicon-based nanomaterials, zinc oxide nanoparticles and nano-enabled hydrogels to help plants cope with water stress. Silicon may support plant water relations and strengthen tissues, while zinc is involved in several important plant enzymes. Certain hydrogels can absorb and retain water, making it available gradually. These materials may have a role in drought management, but they cannot replace irrigation. Their use should be combined with practices such as mulching, moisture conservation and the cultivation of drought-tolerant varieties.

Salinity Stress: Salinity is another major problem for crop production. Excessive salts can interfere with the ability of the roots to absorb water and upset the balance of other necessary nutrients. A high level of sodium can also inhibit the uptake of potassium and damage cells in plants. Some nanomaterials are being investigated for their potential to improve antioxidant defence and help plants maintain a better balance of essential ions. Silicon-based materials, in particular, have received attention for their possible role in improving plant responses to salinity. However, the response depends on the crop, soil conditions and the amount of material applied. Nano-enabled treatments should therefore be considered supplementary tools alongside proper drainage, suitable irrigation practices and salt-tolerant varieties.

Heat Stress: High temperatures can reduce photosynthesis, damage plant cells and affect flowering and grain formation. These effects can lead to considerable yield losses, particularly when heat stress occurs during sensitive growth stages. Some silicon- and selenium-based treatments have been studied for their ability to support antioxidant activity and maintain plant physiological functions under heat stress. However, the effects are not always the same on crops and growing conditions. Selenium is another nutrient that needs careful handling as too much can be toxic. Along with these treatments, farmers need to follow suitable sowing dates, maintain balanced nutrition and select varieties adapted to local temperature conditions.

Nanofertilizers for Better Nutrient Management

One of the most widely discussed applications of nanotechnology in agriculture is the development of nanofertilizers. These products use nanomaterials or nano-enabled delivery systems to supply nutrients to plants. Depending on their formulation, they may help improve nutrient availability or regulate the release of nutrients.

Nano-Nitrogen Fertilizers: Nitrogen is essential for leaf growth, chlorophyll formation and protein synthesis. However, much of the nitrogen applied to agricultural fields may be lost through leaching, volatilization and denitrification. Nano-enabled nitrogen formulations are being developed to improve nutrient delivery and, in some cases, control the rate at which nitrogen becomes available. The aim is to supply nutrients more closely in line with crop demand and reduce avoidable losses. Their performance needs to be compared with conventional nitrogen fertilizers under field conditions before making recommendations for farmers.



Fig: Application of nano-enabled fertilizers in crop production.

Nano-Phosphorus Fertilizers: Phosphorus supports root development, energy transfer and crop establishment. However, in many soils, applied phosphorus reacts with soil minerals and becomes less available to plants. Researchers are investigating nano-enabled phosphorus formulations that may improve nutrient delivery under particular soil conditions. Their effectiveness depends on soil pH, mineral composition and the characteristics of the fertilizer.

Nano-Zinc and Nano-Iron: Zinc and iron are essential micronutrients that contribute to enzyme activity, chlorophyll formation and normal plant growth. Deficiencies can cause poor growth, reduced yields, and visible symptoms such as leaf chlorosis. Researchers are

investigating nano-enabled zinc and iron products as potential nutrient sources. Foliar application can be helpful in some situations as nutrients are applied directly to plant leaves rather than relying solely on soil availability. However, the response depends on the formulation, concentration, crop and weather conditions. These products should be used according to reliable recommendations rather than replacing conventional micronutrient fertilizers without proper evaluation.

Research Examples and Their Practical Importance

Case Study 1: Nano-Enabled Nitrogen Delivery in Rice

Rice cultivation requires careful nitrogen management because nitrogen losses can reduce fertilizer-use efficiency. Researchers have explored formulations such as iron oxide–urea nanocomposites to improve the delivery of nitrogen. The idea is to modify nutrient-release behaviour and make nitrogen available to plants more efficiently. However, the actual benefits depend on the formulation and field conditions.

Practical importance: Better nitrogen management may help reduce fertilizer waste and improve crop performance. Field experiments are needed to determine whether a particular product offers advantages over conventional urea in terms of yield, cost and nutrient recovery.



Case Study 2: Silicon-Based Nanomaterials under Environmental Stress

Interest has been shown in silicon based materials for their potential to support plant growth under drought and salinity conditions. The effects on plant water relations, photosynthesis and antioxidant defence have been investigated. Results are promising in some experimental systems, but the response is dependent on the crop and the method of application.

Practical importance: In cases where benefits have been demonstrated, silicon-based treatments could be used as a complement to water conservation and balanced fertiliser application. Farmers should follow recommendations specific to their crops.

Challenges and Precautions

Despite its potential, nanotechnology faces challenges related to the long-term effects of nanomaterials on soil, water and beneficial microorganisms. Excessive concentrations may cause plant toxicity, while the high cost of some products can limit their use by farmers. Moreover, results obtained under laboratory conditions may differ from field performance. Therefore, proper safety assessment, field testing and economic evaluation are essential before recommending these products for wider agricultural use.

Conclusion

Nanotechnology is opening new possibilities for improving crop nutrition and managing environmental stress. Nanofertilizers, silicon-based materials and nano-sensors may help improve nutrient delivery, support plant growth and make better use of agricultural inputs. However, these technologies should not be viewed as a complete solution to climate change or fertilizer losses. Their success depends on suitable formulations, correct application rates, field performance and environmental safety. With further research and proper evaluation, nanotechnology may complement conventional agricultural practices and contribute to more productive and resource-efficient farming systems.