



Applications of Nanotechnology in Soil Fertility: Towards Smarter and Sustainable Agriculture

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Soil is the foundation of agriculture, supplying plants with essential nutrients, water and physical support. However, continuous cultivation, imbalanced fertilizer application, nutrient depletion, salinity and soil pollution threaten soil fertility and crop productivity. Although conventional fertilizers have significantly increased food production, a considerable proportion of applied nutrients may be lost through leaching, volatilization, runoff or fixation in the soil. Nanotechnology offers new possibilities for improving nutrient management and maintaining soil health. It involves the development and application of materials at an extremely small scale, commonly around 1–100 nanometres (nm). At this scale, materials may exhibit distinctive physical and chemical properties, including a large surface-area-to-volume ratio and enhanced surface reactivity. In agriculture, nanotechnology is being explored for developing nanofertilizers, improving nutrient availability, detecting soil deficiencies, remediating contaminated soils and supporting precision nutrient management. According to Kah et al. (2018), however, the performance and environmental implications of nano-enabled agricultural products must be evaluated carefully before their benefits can be generalized. Nanotechnology should therefore be viewed as a complementary tool for sustainable soil management rather than a replacement for established agricultural practices.

Nanofertilizers: Delivering Nutrients More Efficiently

One of the most promising applications of nanotechnology in soil fertility is the development of nanofertilizers. These are fertilizer formulations that use nanoscale materials, nanoparticles or nanostructured carriers to improve nutrient delivery and availability.

Conventional fertilizers may dissolve rapidly after application, allowing nutrients to move away from the root zone or become unavailable to plants. Nanofertilizers are being investigated to regulate nutrient release, improve delivery efficiency and synchronize nutrient availability with crop demand (Toksha et al., 2021). Nanofertilizer formulations may contain primary nutrients such as nitrogen, phosphorus and potassium, as well as micronutrients such as zinc and iron. Nutrients can be incorporated into nanocarriers, enclosed within suitable coatings or formulated as nanoscale nutrient compounds.

An important example is the development of urea–hydroxyapatite nanohybrids. Kottegoda et al. (2017) demonstrated the potential of this technology for the slow release of nitrogen. Such formulations may help reduce rapid nutrient release and improve synchronization between fertilizer availability and crop requirements. Nanotechnology is also being investigated to improve micronutrient management. Nano-enabled zinc and iron formulations may offer alternative approaches for addressing micronutrient deficiencies, although their effectiveness depends on the formulation, soil conditions, crop species and method of application.

The potential advantages of nanofertilizers include improved nutrient-use efficiency, controlled nutrient release, reduced nutrient losses under suitable conditions and more targeted

correction of deficiencies. Nevertheless, not all nano-enabled products perform better than conventional fertilizers. Their effectiveness and economic value must be demonstrated through field trials.

Improving the Availability of Soil Nutrients

Soil fertility depends not only on the total quantity of nutrients present but also on their availability to plant roots. Soil pH, organic matter, moisture, mineral composition and microbial activity influence nutrient transformations and uptake.

Phosphorus management: Phosphorus may become less available through fixation by iron and aluminium in acidic soils or through reactions with calcium in alkaline soils. Nano-enabled phosphorus formulations and suitable carrier materials are being studied to improve nutrient delivery and reduce losses. Their performance depends on soil chemistry and formulation characteristics.

Nitrogen management: Nitrogen is susceptible to leaching, ammonia volatilization and gaseous losses. Nanostructured coatings and carrier systems may help regulate nutrient release and improve synchronization between nitrogen supply and crop demand. Kottegoda et al. (2017) demonstrated the potential of a nanohybrid approach for controlled nitrogen release.

Micronutrient management: Zinc and iron deficiencies can limit crop growth in many agricultural soils. Nano-enabled formulations are being investigated as alternative delivery systems for these nutrients. Their suitability must be assessed through crop response studies and soil-test-based recommendations.

Mehta et al. (2024) discuss the potential of nanotechnology in plant nutrition, while Kah et al. (2018) emphasize the importance of evaluating nano-enabled products against their conventional counterparts. Therefore, nanotechnology should complement integrated nutrient management, including soil testing, balanced fertilization, organic manures and appropriate irrigation practices.

Nanotechnology for Soil Remediation

Soil contamination by heavy metals, pesticides and industrial pollutants can reduce soil quality, disturb beneficial microorganisms and threaten food safety. Nanomaterials are being investigated for their ability to adsorb, immobilize or transform certain contaminants. Iron-based nanoparticles and other engineered materials may help immobilize selected metal contaminants, reducing their mobility under particular soil conditions. Other nanomaterials are being studied for removing or transforming organic pollutants. Usman et al. (2020) reviewed the potential of nanotechnology in environmental applications, including contaminant management. For example, specially designed iron-based materials may bind certain contaminants or promote chemical reactions that change their mobility. However, immobilization does not necessarily remove a contaminant from the soil; it may simply reduce its mobility or availability. Consequently, the effectiveness of a treatment depends on the type of contaminant, soil characteristics and intended land use. Nanotechnology-based remediation may offer new options for restoring degraded soils, but the movement, persistence and toxicity of the nanomaterials themselves must also be considered. Long-term field studies are essential to determine whether these approaches are safe, effective and economically feasible.

Nanotechnology and Beneficial Soil Microorganisms

A fertile soil is a living ecosystem. Bacteria, fungi, actinomycetes and other soil organisms contribute to decomposition, nutrient cycling, nitrogen fixation and the transformation of nutrients into plant-available forms. Nanotechnology is being explored alongside biological approaches to improve agricultural nutrient management. Biogenic nanomaterials, produced using biological sources or processes, may offer alternative ways to develop agricultural formulations. Reviews of biogenic nanofertilizers highlight their potential contribution to sustainable agriculture, while also identifying the need for further evaluation of their performance and safety (Panorama of Biogenic Nano-Fertilizers, 2023).

Nanocarriers are also being investigated for protecting beneficial microorganisms and improving the delivery of biological inputs. In principle, such technologies could complement biofertilizers containing nitrogen-fixing bacteria and phosphate-solubilizing microorganisms. However, nanoparticles do not automatically improve microbial activity. Their effects depend on their chemical composition, concentration, size and exposure conditions. Some nanomaterials may inhibit beneficial microorganisms or alter soil enzyme activity. Therefore, their compatibility with biofertilizers and native soil microbial communities must be assessed before field application.

Nanosensors for Precision Soil Fertility Management

Traditional soil testing provides valuable information about soil pH, electrical conductivity, organic carbon and nutrient status. However, laboratory analysis may not always provide immediate information about changing field conditions. Nanosensors are being developed to detect selected chemical and biological signals with high sensitivity. In agriculture, nano-enabled sensing technologies are being investigated for monitoring nutrients, moisture, salinity and certain contaminants. When integrated with GPS, remote sensing and digital decision-support systems, these technologies could help identify variations in soil conditions within a field. Farmers may then adjust fertilizer application according to crop requirements and the spatial variability of soil fertility. For instance, if a validated sensing system identifies a region with potentially low nutrient availability, soil testing can confirm the deficiency before corrective fertilizer application. Such site-specific nutrient management may reduce unnecessary fertilizer use and improve nutrient-use efficiency. Although nanosensors offer promising opportunities, their accuracy, affordability, durability and suitability for field conditions must be established before widespread adoption. Reliable measurements and practical recommendations remain essential for successful precision agriculture.

Challenges and Precautions

Despite its potential, nanotechnology in soil fertility has several limitations. The behaviour of nanoparticles depends on their size, shape, surface coating, chemical composition and interactions with clay minerals, organic matter, water and microorganisms. Excessive or inappropriate application may cause phytotoxicity, disturb beneficial soil microorganisms or introduce persistent materials into the environment. Usman et al. (2020) and Kah et al. (2018) highlight the importance of evaluating environmental risks alongside the proposed benefits of nano-enabled technologies. The cost of production, quality control, availability of reliable products and lack of standardized field recommendations are additional challenges. Results obtained under laboratory or greenhouse conditions cannot always be translated directly into farm-level benefits. Farmers should avoid replacing conventional fertilizers solely on the basis of claims made for nano-products. Any product should be used according to its approved label and applicable agricultural recommendations. The appropriate dose, method of application and compatibility with conventional fertilizers must be established for each formulation. Future research should prioritize long-term field trials, crop safety, effects on beneficial soil organisms, environmental fate, cost-effectiveness and region-specific recommendations.

Conclusion

Nanotechnology has the potential to contribute to improved soil fertility through more efficient nutrient delivery, micronutrient management, soil remediation and precision monitoring. These innovations may help reduce avoidable nutrient losses and improve the sustainability of agricultural production. However, soil fertility cannot be restored through technology alone. Maintaining soil organic matter, applying balanced fertilizers, growing suitable cover crops, managing irrigation and protecting beneficial soil organisms remain fundamental practices. The future of nanotechnology in agriculture lies in combining scientific innovation with sound soil management. The goal is not merely to produce more crops, but to nourish plants efficiently while protecting the living soil that sustains agriculture.

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