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NANOTECHNOLOGY IN SOIL FERTILITY MANAGEMENT

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Abstract

Nanotechnology offers a promising approach to managing soil fertility through nanoscale engineering of nutrient delivery. Existing agriculture needs to supply a rising population, even with reduced benefits of traditional methods. The excessive application of chemical fertilisers has contributed to low nutrient-use efficiency and severe environmental issues. Nano-fertilisers are nutrient-carrying nanoparticles that can be used to deliver nutrients at a low rate and only where plants need them, thereby significantly improving efficiency. Their large surface-area-to-volume ratio and distinctive physicochemical characteristics may lead to increased uptake and reduced leaching or volatilisation. Additionally, precision tools and nanosensors can be used to optimise applications.

These developments offer increased yields with fewer inputs and reduced pollution. Nevertheless, there remain risks: nanoparticles can be lethal to soil life or accumulate in food chains, and regulatory frameworks are still evolving. Current research is underway on field trials, biodegradable formulations, and digital integration (e.g., IoT monitoring) to make nanofertilizers safe and useful for sustainable agriculture.

Why Do We Need a New Approach to Soil Fertility?

Soil fertility is at unprecedentedly low levels. The world food demand is increasing at a high rate, with the population steadily growing to almost 9.7-10 billion by 2050 (Goyal et al., 2025; Pagano et al., 2025). Yet conventional fertilisers and practices have already its pushed technology to the limits (Goyal et al., 2025; Nongbet et al., 2022). There has been a significant rise in yield due to traditional mineral fertilizers (N, P, K); however, over 50 per cent of the nutrients applied end up in the environment, wasting resources and polluting the environment. Excessive fertilization contaminates waterways through eutrophication, and nitrous oxide, a very strong greenhouse gas, is released by volatilization, and soil chemistry is disrupted through acidification and salinization (Goyal et al., 2025).

These issues compromise soil health and decrease long-term productivity (El-Ramady et al., 2022; Goyal et al., 2025). Concurrently, biofertilizers and organic amendments, which are environmentally friendly, tend to release nutrients too slowly to meet the demands of high-yield crops (Goyal et al., 2025). In short, current practices either overuse chemicals or failed to provide nutrients efficiently. As global demand is projected to increase by nearly 70 per cent by mid-century, we urgently require more efficient nutrient management (Goyal et al., 2025; Pagano et al., 2025). Nanotechnology has the potential to close this gap by making fertiliser use more precise and efficient. New nanoscale methods can be used to increase yield without additional damage to soils and the environment by designing nutrient delivery to meet plant requirements and reducing losses.

What is Nanotechnology and Why Does Size Matter?

Nanotechnology handles materials and devices that are on the order of billionths of a meter in size (Nongbet et al., 2022). In agriculture, it is the actual engineering of particles and structures within the 1- 100 nanometer scale. At this scale, matter acquires new properties. For example, the surface-area-volume ratio of nanoparticles is very large, and therefore, they are far more reactive and soluble than bulk materials (Nongbet et al., 2022; Yaseen et al., 2025). One nanoparticle can react with numerous other molecules concurrently, making it act quickly chemically or biologically. One of the reviews writes that nano means a billionth part of a meter, which implies that scientists can operate at the level of molecules and atoms to create complex, novel, and distinct structures (Nongbet et al., 2022).

Unique behaviors, including quantum effects, magnetic response, or increased adhesion, are due to the small size. Practically, smaller particles may enter the plant tissues and soil pores more easily, and their surfaces may be functionalized for specific purposes. Chemical, physical, or biological synthesis methods can be used to prepare nanoparticles, which may be composed of metals, carbon nanomaterials, silica, or biopolymers (El-Ramady et al., 2022; Yaseen et al., 2025). They are small, enabling controlled design of release and targeting: nutrients may be loaded or coated at the nanoscale to release slowly and diffuse over an extended period. In summary, the nanoscale is important as it allows fertilizers to be assembled with brand new architectures, wrapping nutrients in small carriers that can be released on demand, instead of dumping large doses of soluble salts into the soil.

Nano-Fertilizers: Smarter Way to Feed Crops

Nanofertilizers are fertilisers designed at the nanoscale to enhance nutrient delivery to plants. In contrast to conventional granules, nanofertilizers typically consist of nutrients attached to or encapsulated within nanoparticles or nanostructured carriers (Nongbet et al., 2022). Indicatively, a nanofertilizer could either be nitrogen, phosphorus, or potassium ions bonded to a silica nanoparticle, a metal oxide particle, or coated in a polymer shell made of biodegradable polymer.

These designs enable the nutrient to be released gradually. According to one review, nanofertilizers are designed materials consisting of nanoparticles of micro- and macronutrients that are released to the plant rhizosphere in a controlled manner (Nongbet et al., 2022). Practically, this implies that every nanoscale particle can be loaded with nutrients and directly introduced into the root zone. Nanoscale carriers, in most cases, contain functional groups or a coating that can interact with plant roots, thereby enhancing uptake.

Because of their tiny size, nanofertilizers have very high surface-area-to-volume ratios, meaning a little goes a long way (Nongbet et al., 2022). Researchers also report that nutrient uptake can be significantly enhanced by nanofertilizers, resulting in higher nutrient-use efficiency relative to bulk fertilisers (Nongbet et al., 2022). Nano-formulations of NPK, micronutrients (Zn, Fe), or nano-chelated nutrients have demonstrated positive effects on seed germination, root development, and overall plant metabolism, and, in many cases, yield increases at low doses in controlled experiments (Nongbet et al., 2022). Through the particle size and coating design, scientists can adjust the speed at which the nutrients are released. For example, urea-coated nanoparticles have a slower nitrogen release rate than plain urea fertiliser, thereby reducing losses (Nongbet et al., 2022). In short, nanofertilizers enhance crop feeding by delivering nutrients in small, user-friendly containers that suit plant requirements and minimise waste (Fig. 1).

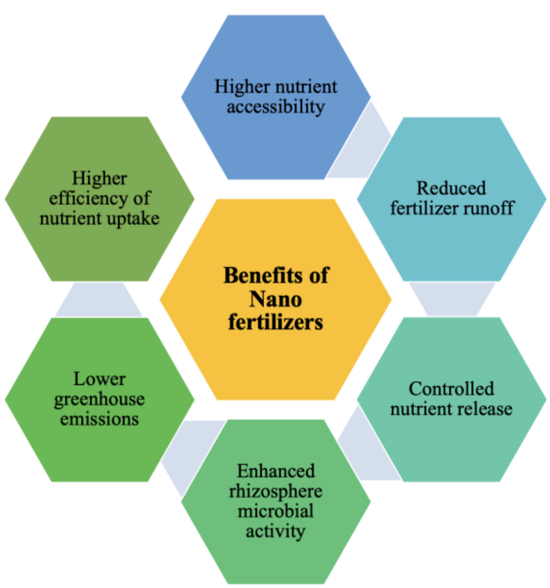

Figure.1: Benefits of nano fertlilizers

Precision Nutrition: Slow Release and Targeted Delivery

Precision nutrition, or the gradual delivery of nutrients over time and at the site where the plants can benefit, is one of the major benefits of nanofertilizers. Active nutrient molecules in nanofertilizers are sometimes encased or adsorbed onto a nanomaterial, in such a way that the release to soil solution is regulated by diffusion or environmental cues (Nongbet et al., 2022; Yaseen et al., 2025). For example, a nutrient may be encapsulated within a nanoporous zeolite or polymer shell that gradually dissolves, releasing a sustained nutrient release rather than a large spike. These slow-release systems have the potential to reduce the leaching of nutrients into groundwater significantly. In a recent review, nano-encapsulation has been explained to provide a controlled release of nutrients: nutrients are slowly released as the nanocarrier and soil moisture or root exudates interact (Nongbet et al., 2022; Yaseen et al., 2025).

Likewise, site-specific delivery of nutrients can be achieved by designing some nanoparticles to deliver their cargo under certain triggers. This, in practice, implies that there is minimal waste of the fertilizer as the nutrients remain available at the root zone as long as they are required, rather than being washed away. Another study has examined the possibility of attaching nanofertilizer to plant growth promoters in a manner that particles are directed actively to roots. Additionally, due to the ease with which nanoparticles can penetrate the plant root cells, they can also be used to deliver micronutrients directly into the plant tissues, given that they are formulated appropriately (Nongbet et al., 2022).

In conclusion, precision nanonutrition is a concept that exploits the exceptional characteristics of nanomaterials, namely high penetration, large reactive surfaces, and functional coatings, to establish stable, controlled nutrient delivery. This targeted and slow-release method is in line with the objectives of precision agriculture, which aims to deliver nutrients to a plant in the most efficient way and with less or no surplus.

Benefits for Soil and Environment

Several environmental and soil health benefits can be achieved through nano-enabled fertilizers. Since nanofertilizers increase nutrient uptake, farmers may also be able to achieve the same yield with reduced overall doses of fertilizer, decreasing fertilizer runoff and greenhouse gas emissions (Goyal et al., 2025; Nongbet et al., 2022). This implies a reduction in the contamination of rivers and lakes and the emission of nitrous oxide to the soil (Goyal et al., 2025; Nongbet et al., 2022). As an example, the controlled release of nitrogen through a nano-coating reduces the rapid conversion to ammonia or nitrate, conserving the soil pH and microbial balance. Nanofertilizers are reported to increase the efficiency of nutrient use and minimize the effects on the environment as opposed to conventional fertilizers (Goyal et al., 2025).

Besides that, nanomaterials also come with ancillary soil benefits. Nanoparticles have the capability of helping remediate soils that have been degraded by binding heavy metals or enhancing soil structure (Yaseen et al., 2025). As an example, metal oxide nanoparticles have the ability to adsorb toxic metals, thus being able to detoxify soil (Yaseen et al., 2025). Nanomaterials may also enhance microbial activity in soil by acting as a habitat or nutrient for useful bacteria. One of the reviews notes that nano-silica and nano-chitosan have the potential of enhancing the viability and colonization of plant growth-promoting rhizobacteria in the rhizosphere, and thus increase nutrient transformations such as nitrogen fixation and phosphate solubilization (Yaseen et al., 2025). Such synergistic processes enhance the general biological quality of soil.

Moreover, nanofertilizers indirectly preserve soil moisture and organic matter by lowering the amount of fertilizers applied and increasing root uptake, as less irrigation and tillage are required to apply high doses of conventional fertilizer. Lastly, field studies have shown that nanofertilized crops tend to be more photosynthetically active and stress resistant, resulting in high yields per acre (Nongbet et al., 2022). To conclude, nanofertilizers are beneficial not only due to increased crop yield but also due to healthier soils and reduced environmental contamination.

Are There Any Risks?

Like any innovative technology, nanofertilizers present certain risks that should be carefully managed. What has made nanoparticles so useful, their small size and reactivity, may also make them toxic when used improperly. Research has established that some nanoparticles at high concentrations are capable of suppressing the growth of plants or killing soil microorganisms (Nongbet et al., 2022). The severity of risk is determined by the material: inorganic metal nanoparticles have a higher likelihood of being toxic than organic nanoparticles (Nongbet et al., 2022).

The issues raised include the buildup of nanoparticles in the food chain, interference with useful soil microorganisms, and the unknown long-term impact on the health of the ecosystem. Critics observe that numerous lab experiments of nanofertilizers do not reflect real-world fields, so it is not clear what may happen to the particles in the environment. No world regulations currently exist on the maximum concentration of nanoparticles used in agriculture, and the techniques used to monitor it are inadequate (Nongbet et al., 2022; Yaseen et al., 2025). Also, other studies indicate that nanoparticles can lead to nano-toxicity due to the binding of nutrients or alteration in the soil chemistry, thereby making them less available or washed away unintentionally (Nongbet et al., 2022). In short, the nanoparticles may unwillingly contaminate soils or kill fauna unless they are dosed properly.

Experts in the industry insist that a substantial use of nano-agrochemicals should be accompanied by rigorous risk evaluation, clear safety limits, and best practice guidelines (Goyal et al., 2025; Nongbet et al., 2022). To mitigate these risks, scientists are making green nanomaterials that are harmlessly degradable and performing experiments on nanoparticle persistence and ecotoxicology (Yaseen et al., 2025). In conclusion, it is evident that although nanofertilizers offer great promise, they need to be strictly regulated, researched, and designed sustainably to avoid adverse effects.

The Future of Soil Fertility

The future of soil fertility management is expected to combine nanotechnology with precision farming and sustainability principles. The future of research will focus on carrying out large-scale field experiments on nano-fertilizers with different crops and climates to confirm their utility and safety in actual farming (Pagano et al., 2025; Yaseen et al., 2025). Biodegradable and green nanomaterials, such as nanoparticles made out of plant extracts or microbial waste, are also being developed by scientists that can deliver nutrients before decomposing harmlessly (Pagano et al., 2025; Yaseen et al., 2025). Digital agriculture integration will be central as nanosensors on the soil can be tied into IoT and GPS systems, and provide real-time data on the soil-nutrient interface. This will allow farmers to apply nano-inputs exactly where and when needed (Yaseen et al., 2025). Innovations in data analytics and remote sensing, e.g., satellite or drone imaging, will collaborate with nano-sensors to optimize fertilizer rates across the field.

Researchers also highlight the use of life-cycle assessment (LCA) for nanofertilizers, ensuring that the impact of production, use, and disposal is all taken into consideration (Yaseen et al., 2025). The future will also be determined by policy and education. Regulations need to be in place to define the safety levels of nanomaterials in agriculture, and the farmers need to be educated on the safe handling of these advanced fertilizers (Pagano et al., 2025; Yaseen et al., 2025). With these measures in place, experts are optimistic that nanotechnology will go a long way in boosting agroecosystem resilience.

A more recent review concludes that, under the right kind of oversight, nanofertilizers can revolutionize soil health and enhance productivity; however, only when there exists a system of responsible innovation (Yaseen et al., 2025). To conclude, the way ahead combines cutting-edge nanoscience, field-scale trials, sustainability evaluation, and partnership between farmers, scientists, and policymakers

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