



Application of Nanotechnology in Protected Cultivation

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Nanotechnology is the science of engineering and utilizing materials at the nanoscale, has emerged as one of the most promising tools in modern agriculture. Protected cultivation is the growing of crops in greenhouses, polyhouses, shade-net houses and low tunnels. This allows Indian farmers to cultivate high-value fruits, vegetables, and flowers under a highly controlled environment throughout the year. However, this method demands very precise management of nutrients, water, pests and the growing climate, which is often expensive and wasteful when met with conventional inputs alone. Because protected structures concentrate high-value crops in a small, enclosed space, they form an ideal setting for the precise, technology-driven inputs that nanotechnology offers. At the nanoscale, materials possess an extremely large surface area and unique properties that make them ideal for delivering nutrients and pesticides more efficiently, strengthening seedlings, and monitoring crop environments in real time.



Nanotechnology for Protected Cultivation

The controlled environment that makes a greenhouse demanding also makes it ideal for precise, nanotechnology-driven inputs. Nano-scale carriers can encapsulate agrochemicals and facilitate controlled, demand-synchronized release, while nanosensors can continuously monitor the condition of the soil, the air and the crop's physiological parameters. Common protected structures include naturally ventilated polyhouses, fan-and-pad greenhouses, insect-proof net houses and plastic low tunnels—settings in which every input carries a higher value and a higher risk if managed poorly. Reviews of nanotechnology in agriculture categorize its uses into four main areas, namely nanofertilizers, nanopesticides, nanosensors and nanobiotechnology, all of which are highly beneficial for protected cultivation (Liu *et al.*, 2021). Key applications and their expected benefits are summarised in Table 1.

Table 1. Applications of nanotechnology in protected cultivation and their expected benefits

Application	Mechanism of Action	Advantages
Nanofertilizers	Nutrients supplied as nanoparticles or held in nano-carriers with slow, controlled release	Higher nutrient-use efficiency; less fertilizer wastage and pollution
Nano crop-protection products	Active ingredient encapsulated for controlled, targeted release	Effective pest and disease control at smaller doses; lower residues
Seed nano-priming	Seeds treated with a nanoparticle suspension before sowing	Faster, uniform germination; stronger seedlings and a better crop stand
Nanosensors	Detect moisture, nutrients, temperature, humidity and disease in real time	Precise, timely inputs, early warning of problems and automation
Nano-improved films and cooling	Nanoparticles added to cooling water and to covering films	Better cooling, light diffusion and protection from ultraviolet rays
Nano-packaging	Films fitted with oxygen scavengers and antimicrobial action	Longer shelf life and reduced post-harvest losses

Nanofertilizers for Precise and Efficient Nutrition

A major problem with conventional fertilizers is their low nutrient-use efficiency, as much of the applied nutrient is not taken up by the plants. Nitrogen, phosphorus and potassium are commonly lost through leaching,

evaporation and fixation in the soil, so that only a fraction is actually taken up. Nanofertilizers address this problem by supplying nutrients either as nanoparticles (NPs) or encapsulated within nano-carriers, which release the nutrient slowly and in synchrony with the plant's demand (Raliya *et al.*, 2018; Guo *et al.*, 2018). Because of their very small size and large surface area, nanofertilizers are absorbed more readily, whether applied to the root zone or sprayed on the leaves, and they can deliver even micronutrients such as zinc, iron and copper in trace but effective concentrations. This controlled and targeted delivery increases nutrient-use efficiency and can reduce the total quantity of fertilizer required, thereby lowering both cost and environmental pollution (Kumar *et al.*, 2021). Greenhouse fertigation, in which fertilizers are supplied through the irrigation water, is already widely used, and nanofertilizers fit naturally into these systems, allowing growers to manage crop nutrition with great precision.

Nano-based Protection against Pests and Diseases

The warm, humid interior of a protected structure can allow insect pests and fungal diseases to multiply rapidly. The frequent application of conventional pesticides is not only expensive but also leaves harmful residues and adversely affects non-target organisms. Nano-formulated crop-protection products offer a smarter alternative. By encapsulating an active ingredient within a nano-carrier, these formulations improve its solubility and stability, protect it from breaking down too quickly, and release it in a slow, controlled manner exactly when it is needed. This approach offers effective pest and disease control using significantly lower doses. It also minimizes airborne spray drift and reduces harmful leaching into the surrounding soil and water. Certain metal and metal-oxide nanoparticles, such as silver, copper and zinc oxide, also possess direct antimicrobial activity against plant pathogens. When used within the enclosed environment of a greenhouse, these targeted formulations can reduce overall pesticide use and help cultivate cleaner, residue-free fruits and vegetables. However, they must be applied carefully, as some nanomaterials can negatively impact beneficial, non-target organisms (Nuruzzaman *et al.*, 2016).

Seed Nano-priming for Enhanced Transplants

Protected cultivation depends heavily on healthy, uniform seedlings raised in the nursery before transplanting. Seed nano-priming, which involves soaking seeds in a prepared suspension of nanoparticles before sowing, has emerged as a simple and affordable way to improve seedling quality. The treatment activates the seed's internal processes, improves water uptake and antioxidant defence, and leads to faster, more uniform germination and stronger seedlings. For example, priming aged rice (*Oryza sativa*) seeds with biogenic silver nanoparticles was shown to enhance germination rates and accelerate the mobilization of stored starch, which is critical for early vegetative growth (Mahakham *et al.*, 2017). In a multi-location study, nanoparticle-mediated seed priming improved the germination, growth, yield and overall quality of watermelon (*Citrullus lanatus*) (Acharya *et al.*, 2020). For greenhouse cultivators, stronger and more uniform seedlings ensure better crop establishment after transplanting, which ultimately leads to a more dependable harvest.

Nano sensors for a Smarter Greenhouse

Achieving precise environmental control is the primary goal of protected cultivation, and nanosensors make this significantly easier. These highly sensitive devices can detect minute changes in soil moisture, nutrient levels, temperature and humidity, and even the early signs of a crop disease, and can report this data in real time (Shang *et al.*, 2019). By networking these sensors, growers can automate irrigation, fertigation and climate control, ensuring crops receive exactly what they need, when they need it. Early and accurate detection of a pathogen or a nutrient shortage allows the grower to act before serious damage occurs, saving both the crop and the cost of unnecessary chemical sprays. Ultimately, nanosensors turn the greenhouse into a smart, data-driven system and a key component of precision farming.

Nanomaterials in Greenhouse Structures, Cooling and Covering Films

Beyond direct crop applications, nanomaterials can improve the greenhouse infrastructure. For example, adding nanoparticles to the water used in evaporative or fog-cooling systems increases the surface-area-to-volume ratio and improves heat transfer, which cools the greenhouse air much more effectively during hot weather. This is especially valuable in the warm Indian plains, where summer heat is a major limitation for protected cultivation. Additionally, nanomaterials are being explored as additives in the plastic films and covers used for greenhouses and tunnels, primarily to enhance light diffusion, block harmful ultraviolet radiation and reduce fogging on the inner surface, thereby creating a better growing environment. In hydroponic systems, which are widely used under protected cultivation, these nanomaterials help in delivering nutrients and maintaining a clean root environment (Ndukwu *et al.*, 2020). Together, these structural improvements augment the crop-level benefits, elevating the overall efficacy of the cultivation system.

Clean Water and Better Post-harvest Handling

High-quality irrigation water is essential for protected cultivation, particularly for drip irrigation and fertigation, where impurities can clog the emitters. To solve this, nanomaterials are increasingly used in water-purification and filtration systems to remove contaminants and harmful microbes, ensuring crops receive clean, safe water

(Singh *et al.*, 2021). The advantages of nanotechnology also extend beyond harvest. Nano-enabled packaging materials, including films fitted with oxygen scavengers, can slow spoilage and extend the shelf life of greenhouse produce such as tomato, capsicum and leafy vegetables. For growers transporting high-value produce to distant markets, an extended shelf life reduces post-harvest losses and improves overall profitability.

Safe and Responsible Use of Nanotechnology

Although nanotechnology provides tremendous benefits, it must be used responsibly. If overused, certain engineered nanomaterials can harm beneficial soil organisms, pollinators and the broader ecosystem, and their long-term environmental fate is still under study. Furthermore, high cost, a lack of standardized products and the need for clear regulations remain practical challenges, especially for smallholders in India (Pandey, 2018). Farmers are therefore advised to use only approved, well-tested nano-products, to follow the recommended doses strictly, and to adopt them under expert guidance until standard practices become widely available.

Conclusion

Protected cultivation has created new opportunities for Indian farmers to grow high-value crops that offer better quality and higher economic returns. The integration of nanotechnology can make this system even more precise, productive and sustainable. Growers can significantly reduce their input usage through various nano-innovations. These include nanofertilizers for efficient nutrient delivery, nano-formulated products for effective protection at lower doses, seed nano-priming that raises healthy seedlings, nanosensors for real-time greenhouse monitoring, and nanomaterials for better cooling, coverings and packaging. To the farming community, the message is simple: when used wisely and responsibly, nanotechnology is a valuable partner for the future of protected cultivation. It enables the production of more food on less land with fewer inputs, while safeguarding our soil, water and overall health.

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