Applications of Nano-Agrochemicals in Agriculture

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Agricultural sector is facing enormous challenge of increasing crop productivity and efficiency to meet the ever-increasing demand for the rapidly growing world population under limited arable land**.** Traditional agricultural practices alone are often unable to meet these demands, leading to the exploration of innovative technologies to enhance agricultural productivity. One such technology that holds great promise is the application of nano-agrochemicals, which have shown tremendous potential in improving the physiological efficiency of agricultural crops. Nano-agrochemicals are a recent development in the field of nanotechnology that involves the synthesis and application of nanoscale materials in agriculture. Their small size (1 to 100 nm) allows for increased surface area and enhanced reactivity, leading to improved solubility, stability, and bioavailability (Das et al., 2023).

Nano-agrochemicals offer several mechanisms by which they can improve the physiological efficiency of crops. Enhancing physiological efficiency is essential to optimize resource utilization, minimize wastage, and reduce the environmental impact of agricultural practices. Nano-agrochemicals can enhance nutrient uptake and utilization by crops. Nanoscale formulations of fertilizers and micronutrients can be engineered to improve their solubility and dispersibility, making them more readily available to plants. Additionally, nano-sized carriers can protect nutrients from leaching and volatilization, ensuring their efficient delivery to plant roots. Furthermore, nanoscale materials can be functionalized to release nutrients gradually, providing a sustained nutrient supply to plants over an extended period. Nano-agrochemicals can enhance crop protection against pests and diseases. Nanoscale formulations of pesticides and fungicides can be designed to have increased efficacy, as their small size allows for better penetration into plant tissues and improved targeting of pests and pathogens. Moreover, nano-agrochemicals can be functionalized with specific molecules to provide controlled release of active ingredients, ensuring prolonged protection and reducing the frequency of applications (Singh and Kalia 2019). Likewise, nano-agrochemicals can enhance crop tolerance to environmental stresses, such as salinity, heat, and heavy metals.

The use of nano-agrochemicals holds great potential in improving the physiological efficiency of agricultural crops and offer innovative solutions to address the challenges faced by modern agriculture. However, it is crucial to ensure on their safety, environmental impact, and long-term effects before their widespread adoption. Continued exploration and development of nano-agrochemicals can pave the way for a more sustainable and productive agricultural future.

Type of nano-agrochemicals:

Nano-fertilizers: It has been getting much attention in field of agriculture over the conventional chemical fertilizers due to its potential to increase yield, improve soil fertility, maintain sustainability of the environments and make a favorable surroundings for soil's beneficial microorganisms. IFFCO Nano

Urea is a nano-fertilizer which provides the nitrogen to the plant. It is nanotechnology based innovative agri-input (fertilizer) which particle size about 20-50 nm. Hence, Nano urea increases the availability of nitrogen to crop by more than 80% resulting in higher nutrient use efficiency, minimizing the environmental pollution and fight with climate change, Through the reducing the loss of nutrients from the field of agriculture in the form of leaching and gaseous emission.

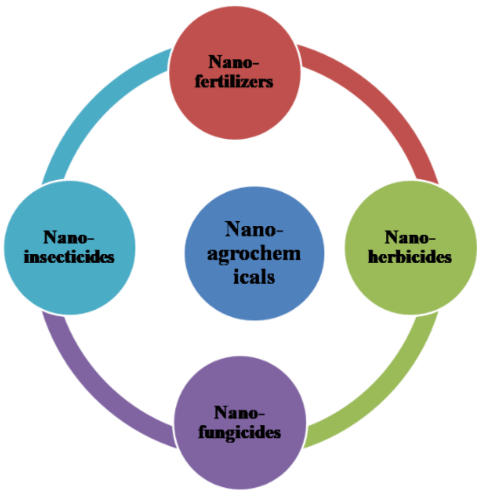


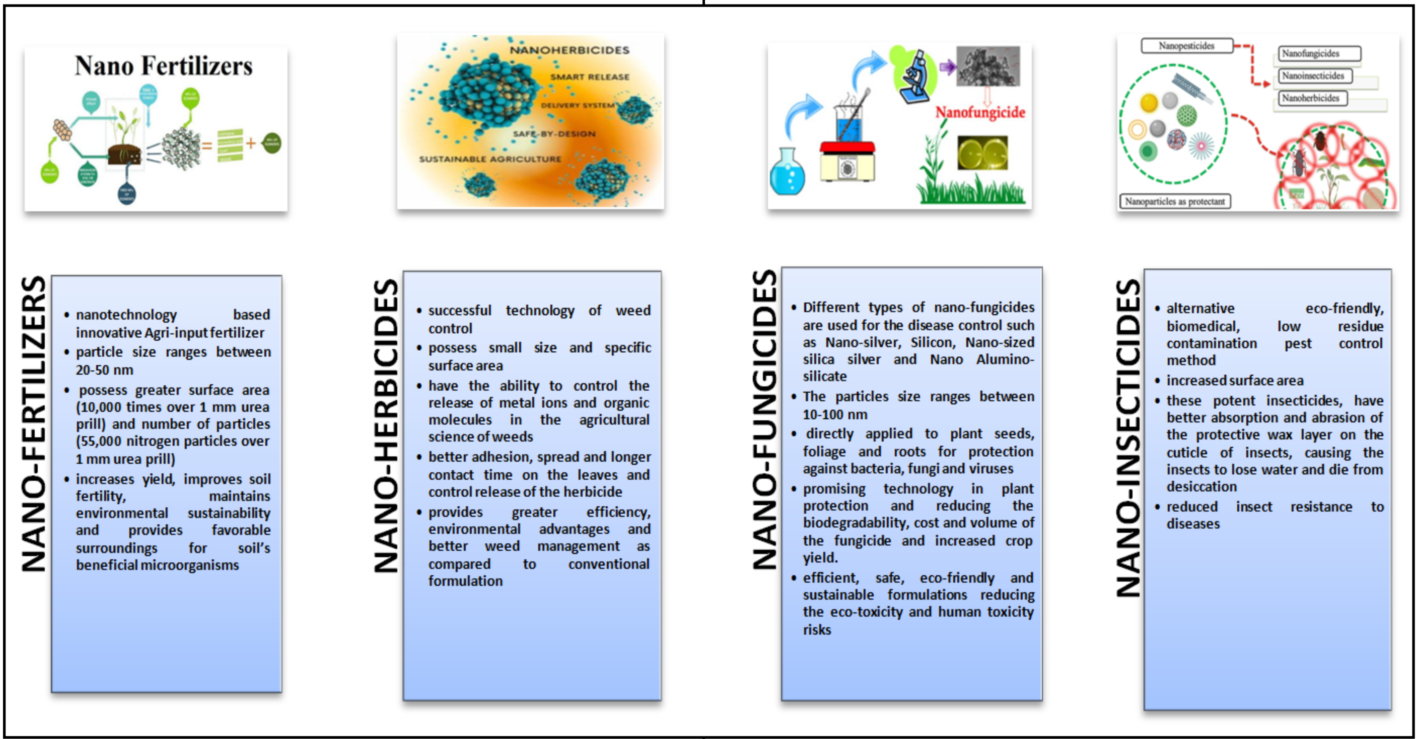
Fig.1: Diagrammatic representation of type of nano-agrochemicals

Nano-herbicides: In agriculture field nanotechnology has emerged as useful technology to weed control. There have been reported several nano-herbicide for weed control in recent time. It can be premeditated from organic, inorganic, or hybrid materials. These nano-herbicides have distinctive properties such as small size, specific surface area, and the ability to control the release of metal ions and organic molecules in the agricultural science of weeds. Nano-herbicide has better ability to adhesion, spread and longer contact time on the leaves and control release of the herbicide. Several studies have reported the ability of nano-herbicides to provide greater efficiency, environmental advantages and better weed management compared to conventional formulation.

Nano-fungicides: At present time, due to the use of conventional chemicals for the control of disease have shown that a negative impact on environment. So the interest in efficient, safe, eco-friendly and sustainable agriculture fungicide formulations has been developed to reduce the eco-toxicity and human toxicity risks(Jeya et al., 2022). There are different type of nanotechnology based nano-fungicide are used for the disease control such as Nano-silver, Silicon, Nano-sized silica silver and Nano Alumino-silicate. The particles size of the Nano-fungicide are the range between 10-100 nm, and it can be directly applied to plant seeds, foliage and roots for protection against bacteria, fungi and viruses (Jeya et al., 2022). Recently, silver nanoparticles have found potential to control disease and increased in popularity, due to "green synthesis" production in plants, bacteria, fungi and yeast. Silver nanoparticles have shown antifungal inhibition by well diffusion assay. So, it is a promising technology in plant protection and reducing the biodegradability, cost and volume of the fungicide and increased crop yield.

Nano-insecticides: Excessive uses of conventional insecticides are the source of contamination and have negative impacts on human health and other species. Thus, it is required to develop alternative pest control methods for a sustainable ecosystem. The Nano-insecticides are the best alternative of the conventional insecticide because it have eco-friendly, biomedical properties, low residue contamination. Potent antimicrobial activities of ZnO NPs synthesized by different methods were due to their increased surface area. As potent insecticides, ZnO NPs can be attributed to the absorption and abrasion of the protective wax layer on the cuticle of insects, causing the insects to lose water and die from desiccation.

Fig.2: Different types of nano-agrochemicals



Potential of NPs against environmental stresses

Abiotic stress

Recent research has shown the promising potential of nanotechnology to improve the agriculture sector by increasing the efficiency of agricultural inputs and offering solutions to agricultural and environment problems for improving food productivity and security. Abiotic stress is the primary cause of crop loss worldwide and reduces the average yield of most major crop plants by > 50%. Abiotic stress leads to morphological, physiological, biochemical, and molecular changes in plants that adversely affect their growth, development, and productivity (Zhao et al., 2020).

It is known that ROS (Reactive oxygen species) are formed by the plants at high levels due to abiotic stress within different organelles and leading to cellular damage. Over-accumulated ROS in plants results in damaged cell membranes, DNA, protein, and other cell components and therefore the inhibition of plant growth. These ROS can be scavenged by nanoparticles such as CeO_2, C60, and Fe_2O_3 NPs. Thus, plant engineered with these NPs showed better performance under stress conditions. For example, Nano-particle CeO_2 at very lowconcentrations (5 µM) effectively reduces ROS levels and protect chloroplasts and under high salinity the antioxidant activity of polyacrylic-acid-coated CeO_2NPs (35% Ce^{3+}/Ce^{4+}, 10 nm, 17 mV, 50 mg/L) with superoxide dismutaseand catalaseactivities maintained the photosynthetic ability of *Arabidopsis*. Enzyme-mimicking fullerol NP was also alleviate the oxidative stress of sugar beet under drought stress, by serving as an additional intercellular water supply.

Biotic stress

Biotic stresses prompted by phytopathogens and pests impose tremendous losses in agriculture and are major threats to worldwide food security. Nanotechnology offers promising solutions to mitigate biotic stress on plants, increasing plant tolerance to the stressor, for the remediation of environmental contaminants, and to protect plants against pathogens (Silva et al., 2022). Several NPs, such as AgNP, CuNP, AlNP, CNP and MgNP etc exhibit antibacterial and pest control functions.

Silver based Nano particles

The increasing prevalence of fungi and pests to resistance current pesticide made it clear that new methods (Nano-pesticides) of crop protection were required. So Nano silver is the most studied and utilized nano particles for bio-system. Because, of high antibacterial effects, a broad spectrum of antimicrobial activities and more adhesive on bacteria and fungus hence are better fungicide. For example, Ag@dsDNA@GO (DNA-directed silver (Ag) nanoparticles grown on grapheme oxide composites at 16 mg/L significantly decreased the activity of cultured *Xanthomonas perforans*.

Copper based Nano particles

Cu ions are well known for antibacterial and antifungal activities. In a greenhouse study, $Cu_3(PO_4)_2 \cdot 3H_2O$ nanosheets (10 mg/L) significantly suppressed fungal disease, as measured by yield and a 58% decrease in disease progression. The insecticidal activity of Cu NPs has also been demonstrated. Effects of CuO NPs on Bt-transgenic cotton and conventional cotton have also been investigated. At a dose of 10 mg/L the particles enhanced the expression of exogenous genes encoding Bt toxin in cotton plant tissues, thereby improving resistance.

Magnesium based Nano particles

A new MgO nano particles have biologically more active and relatively more environmentally safe pesticide. For example, Zhao *et al.*, (2020) showed that MgO NPs at 200 or 250 mg/L effectively suppressed *R. solanacearum* which induced tobacco bacterial wilt. *Ralstonia solanacearum, X. alfalfa, Pseudomonas syringae* and *E. coli* etc. disease-causing organism were significantly control by the MgO based nano particles.

Nano-fertilization to Enhance Nutrient Use Efficiency and Productivity of Crop Plants

Nano-fertilizers (NFs) are nutrient carriers developed by using the substrates with nano dimensions (1–100 nm), which have extensive surface area and can hold abundance of nutrients to be released slowly and steadily. In the case of conventional fertilizers, nutrient use efficiency hardly exceeds 30–35%, 18–20%, and 35–40% for N, P, and K, respectively, and these estimates remain constant for the past several decade, whereas the nano-clay-based fertilizer formulations are capable of releasing N for a much longer period of time (>1000 h) than the conventional fertilizers (<500 h). Nano-fertilizers may contain NPs (nano particle suspensions) of zinc, silica, iron and titanium dioxides, ZnCdSe/ZnS core-shell QDs, InP/ZnS core-shell QDs, Mn/ZnSe QDs, gold nano-rods, core-shell QDs (quantum dots) etc. Since they provide a larger surface area for reaction and a prolonged availability of nutrients to the crop plant, this situation favors quality parameters, such as protein, oil, and sugar contents, by enhancing the rate of reaction or synthesis process in the plant system, as observed in various crops. The use of NFs not only enhances the nutrient use efficiency but also reduces the frequency of fertilizer application and consequently the soil toxicity and other potential negative effects associated with excessive use of chemicals (Kumar et al., 2023). The favorable effects of use of NFs over CFs (conventional fertilizers) in enhancing physiological processes such as improved germination, seed vigor, establishment and photosynthesis etc. have been reported. For example, Use of zinc (4%) + iron (4%) NFs have resulted in increased rate of germination, seedling vigor and establishment of red bean seedlings. Use of low concentration (10 g ml^{-1}) of Ag NFs promoted germination in lentil, while 500 ppm of TiO_2 resulted in enhanced germination in *Cicer arietinum*. Enhanced photosynthesis by enhanced pigment production and stimulated RUBISCO activity was reported in barley. Nano Fe and Zn application enhancing nitrogen metabolism, cell multiplication, photosynthesis, and auxin synthesis have been also reported in chickpea.

Conclusion

In order to fulfill sustainable development goals, crop production must be elevated and the pollutants and greenhouse gasses emissions associated with farming pastime need to be decreased. We recommend that advances in the utility of nanotechnology have the ability to improve physiological efficiency crops. Regulated and sustained unleash of nutrients assists in raising the nutrient use efficiencies and as well as improve the insect pest control efficiency over the conventional agro-chemicals. Slow or controlled-release and carrier delivery properties of nano-agrochemicals enhance the crop yields, soil health, and lower nutrient loss compared with traditional fertilizers.

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