Rationale of Nanotechnology in Agronomic System

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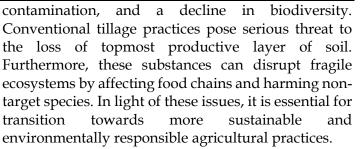
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Introduction

Food and Agriculture Organization (FAO) has reported an 50% increase in food demand by 2050. This demand gap is filled with intensive agricultural practices by depleting natural resources at a faster rate impacting sustainable agriculture. The need for intense modifications in food production system has grown to a level to increase global food productivity to the tune of three billion tonnes with huge applications of agrochemicals. The overuse of fertilizers and pesticides has increased the risk of eutrophication in surface water bodies and groundwater, leading to a compromised ecosystem integrity. This disruption of natural cycles has adversely affected the life cycles of various organisms. As a result, the degradation of ecosystems has contributed to the emergence of significant human health issues in recent times. Further increased agrochemical applications obstructed agricultural productivity and sustainability with deuteriation in environmental quality. Nanotechnology based approaches can help small and marginal farmers tackle this most emerging challenges. Nanoscience helps in achieving sustainable development goals for hunger by increasing the efficiency of agricultural system. This article deciphers recent agronomic practices and their challenges and briefly describes nanotechnological approaches for overcoming these challenges (Table 1).

Conventional Practices

Traditional agricultural methods largely rely on the use of agrochemicals, such as fertilizers and pesticides and energy exhaustive farm operations using machineries to improve crop production and protect against pests and diseases. Although this strategy may appear effective in the short term, it carries significant disadvantages. The application of agrochemicals is often inefficient, requiring large amounts to achieve the desired results. The associated high costs in machineries, chemicals, labours create a substantial financial strain on farmers, especially in developing countries. Additionally, these chemicals pose serious health risks, leading to various health issues, including respiratory problems and cancer. The environmental impact is equally concerning, as agrochemicals contribute to soil degradation, water contamination, and a decline in biodiversity. Conventional tillage practices pose serious threat to the loss of topmost productive layer of soil. Furthermore, these substances can disrupt fragile ecosystems by affecting food chains and harming non-target species. In light of these issues, it is essential for transition towards more sustainable and environmentally responsible agricultural practices.

Modern Agricultural Practices

Modern agricultural techniques, including crop rotation, intercropping, and the application of organic fertilizers sourced from animal, plant, and mineral origins, signify a notable advancement in sustainable farming. These approaches enhance soil fertility, decrease dependence on synthetic inputs, and promote ecosystem vitality. Despite the numerous benefits these practices provide, they also have certain drawbacks. For example, organic farming typically demands more labor-intensive methods and may yield lower productivity compared to traditional practices. Furthermore, the success of organic pest management techniques can vary significantly. Both conventional and modern agricultural methods face considerable challenges in achieving global food security and environmental sustainability. The widespread application of agrochemicals has jeopardized human health and ecosystems, leading to the rise of pesticide and herbicide-resistant pests and weeds. These interrelated issues highlight the pressing necessity for innovative and sustainable agricultural strategies. To address these challenges and fully realize the potential of modern agriculture, researchers are exploring the applications of nanotechnology. By harnessing the unique properties of materials at the nanoscale, scientists are developing innovative solutions that address the complexities of food production while minimizing environmental impact.

Nanotechnology in Agronomic system

Nanotechnology represents a pioneering domain that involves the manipulation of matter at the atomic and molecular levels, enabling the creation of materials and devices with extraordinary characteristics. The integration of nanoscience and technology encompasses the creation and operation of materials at the nanoscale, facilitating the

manipulation and development of innovative tools, materials, and structures at the molecular level. This field integrates knowledge from biology, materials science, and information technology. As an interdisciplinary science, it possesses significant potential to tackle challenges that conventional methods are unable to resolve. Although living organisms' function at the nanoscale, researchers are still in the nascent phases of developing tools and technologies that can fully exploit this potential. The promise of nanotechnology is evident across various sectors, including agriculture, where its applications extend from enhancing food production and safety to optimizing farming practices.

Table 1. Comparison of different agricultural practices for sustainable agriculture

Agriculture System	Conventional agriculture Practices	Modern Agriculture practices	Nano-based agriculture practices
Methods used	These practices are based on use of distinct types of chemicals	These practices involve mixed cropping, crop rotation, companion planting and organic compost	These practices are based on use of active ingredients in the form of distinct types of nanomaterials
Fertility of soil	Poor fertility	Augmented the fertility of soil by improving the nutrients content	Increased the nutrients content of soil thereby significantly augmented the soil fertility
Types of fertilizers	Fertilizers used are mainly inorganic	These practices use organic fertilizers	Both inorganic as well as organic fertilizers are used in these practices
Concentration of active ingredients	Agrochemicals are required in very high amount	These practices require moderate amount of agrochemical	These practices require very low number of agrochemicals
Nutrient content	Soil contains scarce amount of nutrients	Soil contains all nutrients required for growth of crops	Soil is very rich in nutrients
Efficiency	These practices show poor efficiency	These practices show high efficiency	These practices show exceptional high efficiency
Targeted/non-targeted	Agrochemicals used in these practices are non-targeted	Agrochemicals used in these practices are also non-targeted	Agrochemicals used in these practices are targeted
Stability	Stability of spraying of agrochemicals is very less	Stability of spraying of agrochemicals is better than conventional practices	Stability of spraying of agrochemicals is good
Toxicity	Very hazardous consequently, increases the risk of cancer, reproductive toxicity and neuronal ailments. These also increase the risk of eutrophication in water bodies.	These practices minimum toxicity	These practices show moderately but green nanomaterials do not cause toxicity
Effect on soil	Fertile but soon become infertile due to exploitation.	These practices keep soil fertile but may increase the prevalence of deforestation and soil erosion	Nanomaterials based approaches significantly enhance fertility of soil

Significance of Nanotechnology

Nanotechnology has made significant strides in overcoming agricultural challenges by employing nanotools and nanodevices. The application of nanomaterials, including carbon-based and metallic nanoparticles, is notable for their extensive surface area, which facilitates targeted nutrient delivery, thereby enhancing crop yields while reducing environmental repercussions. Engineered nanomaterials (ENMs) play a crucial role in advancing plant breeding, genetic modification, and the sustainability of crops by optimizing the application of

agrochemicals. For instance, nanoparticles of zinc and copper have been shown to promote seed germination and increase crop productivity through improved nutrient absorption and enhanced photosynthetic performance. Furthermore, ENMs are also employed in sensors that enable accurate monitoring of crop health. Engineered nanomaterials (ENMs) have the potential to promote agricultural sustainability by (i) enhancing soil structure and decreasing dependence on nitrogen fertilizers, (ii) increasing seed germination rates through the application of Zn and Cu nanoparticles on seeds, which proves to be more effective than conventional methods involving potassium chloride, potassium nitrate, or polyethylene glycol (PEG), and (iii) improving crop yields via foliar applications of ENMs such as nano Zn, ZnO, and TiO2, which facilitate efficient and precise absorption of agricultural chemicals.

Importance of Nanotechnology over Bulk materials

Nanomaterials exhibit distinctive characteristics, including an increased surface area, improved ion adsorption, and enhanced cation exchange capacity when compared to bulk materials. In contrast to bulk materials, nanomaterials reveal a significant number of surface atoms, which boosts their reactivity and effectiveness in agricultural contexts. Engineered nanomaterials (ENMs) present an innovative strategy for agriculture by overcoming biological barriers, optimizing the targeted delivery of nutrients and pesticides, and strengthening crop resilience through precise and controlled release mechanisms. These attributes position ENMs as a highly promising avenue for the evolution of agricultural methodologies.

Applications of Nanotechnology in agriculture

- Nano-fertilizers
- Nano-carriers for targeted drug delivery
- Insect-Pest management
- Climatic adoption
- Nanosensors\Nanobiosensors for Precision agriculture

Conclusion

In summary, the incorporation of nanotechnology into agriculture signifies a groundbreaking strategy for tackling the intricate challenges encountered by both traditional and modern farming methods. With the escalating global demand for food, the drawbacks of conventional practices such as excessive reliance on agrochemicals and the consequent environmental harm, highlight the pressing necessity for innovative alternatives. Nanotechnology presents a viable option for boosting agricultural efficiency while fostering sustainability. By leveraging the distinctive characteristics of nanomaterials, such as their extensive surface area and precise delivery mechanisms, researchers are creating sophisticated tools and methodologies that enhance nutrient utilization, improve soil health, and strengthen crop resilience. Furthermore, the use of engineered nanomaterials (ENMs) in plant breeding, genetic enhancement, and precision agriculture paves the way for more effective and environmentally conscious farming techniques. As the domain of nanotechnology progresses, its capacity to transform agriculture and support global food security becomes increasingly apparent, establishing it as a crucial element of future agricultural initiatives.

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