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ROLE OF NANO MATERIALS ON THE ENHANCEMENT OF AGRICULTURAL PRODUCTION

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Abstract: Nanomaterials have emerged as promising tools in agricultural production, offering novel solutions to enhance crop yield, improve soil health, and reduce environmental impacts. Their unique physicochemical properties, such as high surface area and reactivity, enable precise delivery systems for fertilizers, pesticides, and herbicides, minimizing resource wastage and contamination. Nanocarriers allow for controlled release of nutrients and chemicals, improving efficiency and reducing the need for excessive chemical use. Additionally, Nano sensors are being developed for real-time monitoring of soil and plant health, enabling better decision-making for irrigation, pest control, and nutrient management. Metal and metal oxide nanoparticles, such as zinc and titanium oxide, have been shown to promote plant growth and protect crops from diseases and pests. Despite these advantages, concerns about the environmental and health risks associated with nanomaterial use in agriculture persist, necessitating more research on their long-term safety. Regulatory frameworks also need to evolve to address these challenges. Overall, nanomaterials hold significant potential for revolutionizing sustainable agriculture by increasing productivity, improving resource use efficiency, and reducing the ecological footprint of agricultural practices. Further research is essential to optimize their use and ensure their safety in agricultural ecosystems.

Keywords: Nanomaterials; Agriculture; Nano-fertilizers; Nano-pesticides; Sustainable farming.

1. INTRODUCTION

Nanomaterials are extremely small materials with sizes ranging from 1 to 100 nanometers (a nanometer is one billionth of a meter) [1]. Due to their tiny size, they often have unique properties compared to larger-scale materials. These properties can include increased strength, lighter weight, or better chemical reactivity. Nanomaterials are used in a variety of fields such as medicine, electronics, and energy to create more efficient or advanced products [2]. In agriculture, nanomaterials are microscopic compounds. used to improve farming and crop production. They can help in various ways, such as making fertilizers and pesticides more effective, improving soil quality, or protecting plants from diseases and pests. Because nanomaterials are so small, they can be designed to deliver nutrients or chemicals precisely where needed, leading to better crop yields and more sustainable farming practices [3]. Nanomaterials can be broadly categorized into nanoparticles, nanotubes, and nanocomposites. Their small size allows them to interact with plants, soil, and pests at a molecular level, making them highly effective for various applications in agriculture. Enhanced Fertilizers and Pesticides: Traditional fertilizers and pesticides can sometimes be inefficient, leading to waste and environmental issues [4]. Nanomaterials can improve their delivery and efficiency. For example, nanosized fertilizers can release nutrients slowly, ensuring that plants receive a steady supply of nutrients over time. This controlled release can reduce the amount of fertilizer needed and minimize environmental runoff. Similarly, nanopesticides can target pests more precisely, reducing the overall amount of chemicals used and limiting their impact on non-target organisms [5]. Soil Improvement: Nanomaterials can enhance soil quality by improving its structure and increasing its water and nutrient-holding capacity. For instance, nanomaterials such as carbon nanotubes can help soil retain moisture, which is crucial in drought-prone areas [6]. Additionally, nanomaterials can help in the remediation of contaminated soils by binding to and removing harmful substances, making the soil healthier for plant growth. Disease and Pest Control: Nanomaterials can be used to develop advanced treatments for plant diseases and pest infestations [7]. Nanoparticles can be designed to deliver specific treatments directly to affected plant tissues, increasing the effectiveness of disease control measures. Furthermore, nanomaterials can act as insect repellents or disrupt the lifecycle of pests, reducing the need for broad-spectrum chemical pesticides. Precision Agriculture: Nanomaterials enable precision agriculture, which involves using detailed data to manage crops more effectively [8]. Sensors incorporating nanomaterials can monitor plant health, soil conditions, and other important factors in real time. This data allows farmers to make informed decisions and apply resources more efficiently, leading to higher crop yields and reduced environmental [9].

2. NANOMATERIALS FOR AGRICULTURAL APPLICATION

The tribal communities of Odisha have long relied on the biodiversity around them for health and well-being, particularly through the use of medicinal plants[9]. Their knowledge of these plants has been passed down for generations and is deeply intertwined with their cultural and spiritual practices[10]. Medicinal plants play a crucial role in treating common ailments, chronic conditions, and spiritual needs. Understanding the cultivation, medicinal value, and uses of these plants can provide insights into both traditional healthcare systems and modern herbal practices. In recent years, nanotechnology with smart nanoscale carriers for effective delivery of macro- and micronutrients, plant growth regulators, pesticides and fertilizers has become an efficient method for sustainable agriculture [10]. Nano-carriers prevent chemical discharge and solve environmental issues by securing plant roots to the organic materials and soil structure in the ecosystem. These aids in enhancing the bioavailability of active ingredients to the plant while lowering the effort and waste product [11]. Similar to nano herbicides, nano pesticides are also garnering recognition for replacing traditional pesticides due to their enhanced efficacy against a variety of pests and potential for tailored action, which lowers the environmental toxicity. In a study with Drosophila melanogaster as a model organism, the anti-pest activity of chitosan loaded with permethrin and Spinosad was tested at various doses. It demonstrated that the combination of Spinosad and permethrin in chitosan is more effective than either compound alone, suggesting that nano formulations may be used for pest control management [13]. Further, the association of chitosan with zinc helps enhance the plant’s immunity., the formulation of zinc and chitosan nanoparticles increases the antioxidants and content of lignin in maize crops to elevate disease control [14]. Red-seaweed-extract-derived silver nanoparticles are suited for use in the formulation of nano pesticides due to their antibacterial and antifungal properties [15]. As crop plants can only absorb 30–50% of chemical fertilizers, a sizable portion of the input remains in the soil, which causes soil sterility and ground water contamination. Due to saturation, fertilizer efficiency thus declines over time [16]. Nano fertilizers have efficiency to reduce the nutrient loss via controlled release and thus may minimize the amount of fertilizer application in the field [17]. Many nanoparticles themselves work as nano fertilizers or as a nano encapsulating agent to transform conventional fertilizer into nano fertilizers [18]. Figure 1 shows different nanomaterials used in agricalture

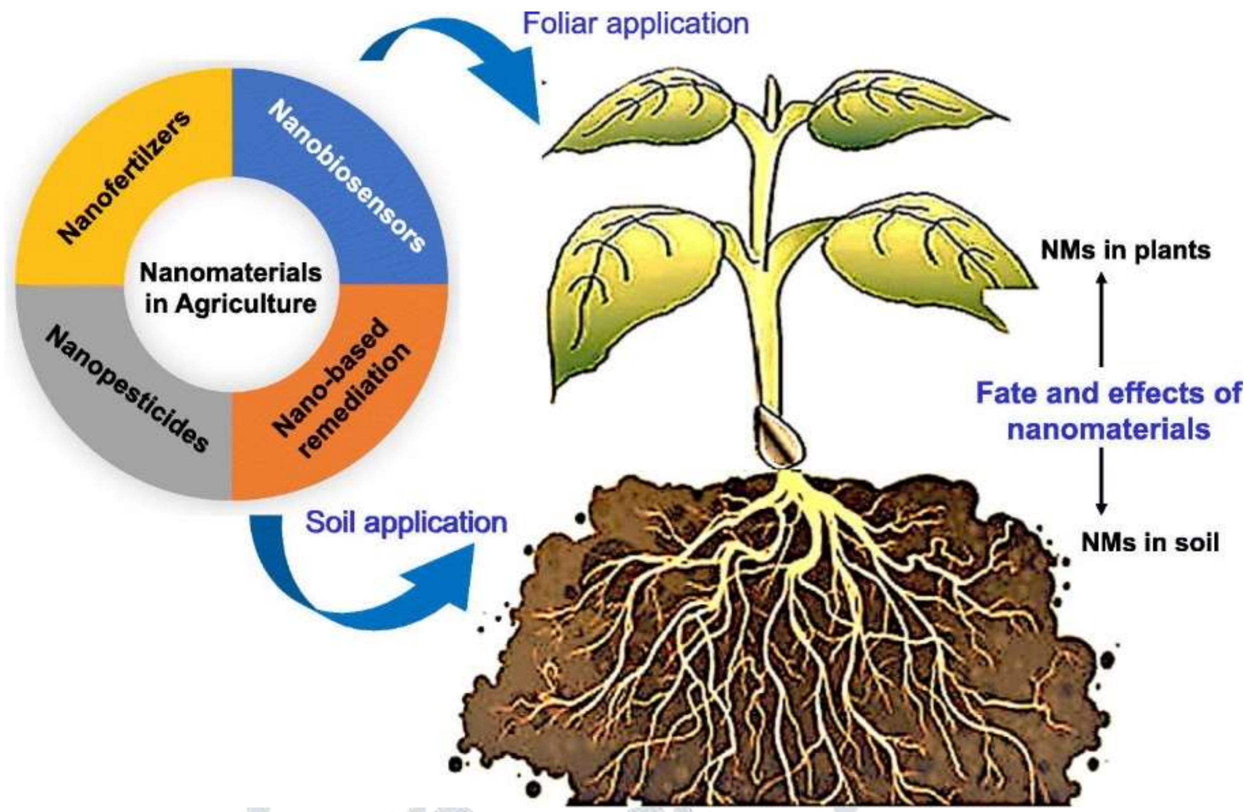

Figure 1: Nanomaterials in agricalture

2.1 Improved Fertilizer Efficiency

Increased Solubility: Nanomaterials can enhance the solubility of nutrients, making them more readily available to plants. For example, nanostructured fertilizers can dissolve more easily in water, improving nutrient absorption by plant roots [19]. Nanomaterials can help reduce nutrient leaching, where nutrients are lost to the environment before plants can use them. By improving the stability and retention of nutrients in the soil, nanomaterials help ensure that fertilizers are used more efficiently [20].

Chemical fertilizers are indispensable for modern agricultural systems. However, the efficiency of synthetic chemical products has been decreasing for decades, accompanied by water pollution, soil contamination and greenhouse gas emissions [21]. Nanotechnology could pave the way for sustainable agriculture (Figure 2).

Nano fertilizers are mineral nutrients manufactured mainly by encapsulation with nanoparticles and can be classified into macronutrients and micronutrients [22]. Macronutrients such as carbon (C), nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), sulfur (S) and magnesium (Mg) have been encapsulated by different nanomaterials, to improve crop absorption of fertilizers and decrease fertilizer outflow [23]. The high specific surface area, high stability and excellent biocompatibility of nanoparticles provide fertilizer composites with increased release efficiency [23]. For example, urea-hydroxyapatite (HA) nanoparticles have exhibited great potential for prolonging the release time and reducing the consumption of nitrogen fertilizers. Urea obtains the advantages of nanoparticles by interacting with amine and carbonyl groups of HA nanoparticles. Field trial data have shown that, compared with pure urea, nanohybrids of urea and HA increase agronomic nitrogen use efficiency by approximately 30% [15]. In addition, numerous studies have revealed that the high specific surface area and density of NPs endow nanohybrids with high reactivity. The application of nano fertilizers has great promise for promoting fertilizer absorption and increasing crop yields [23]. In conclusion, the nanohybrids mentioned above, with plentiful pores and less volume, facilitate nutrient uptake. Fertilizers encapsulated by nanoparticles, especially porous nanoparticles, are hardly damaged by environmental factors such as rain and wind while those compounds are easily transferred into plant cells. This feature prolongs the fertilizer release time and improves soil physical and chemical properties. Moreover, chemical reactions of nanoparticles and fertilizers decrease and homogenize the particles size of fertilizers. This process endows nano fertilizers with stability and high specific surface area, which significantly increases the efficiency of fertilizers.

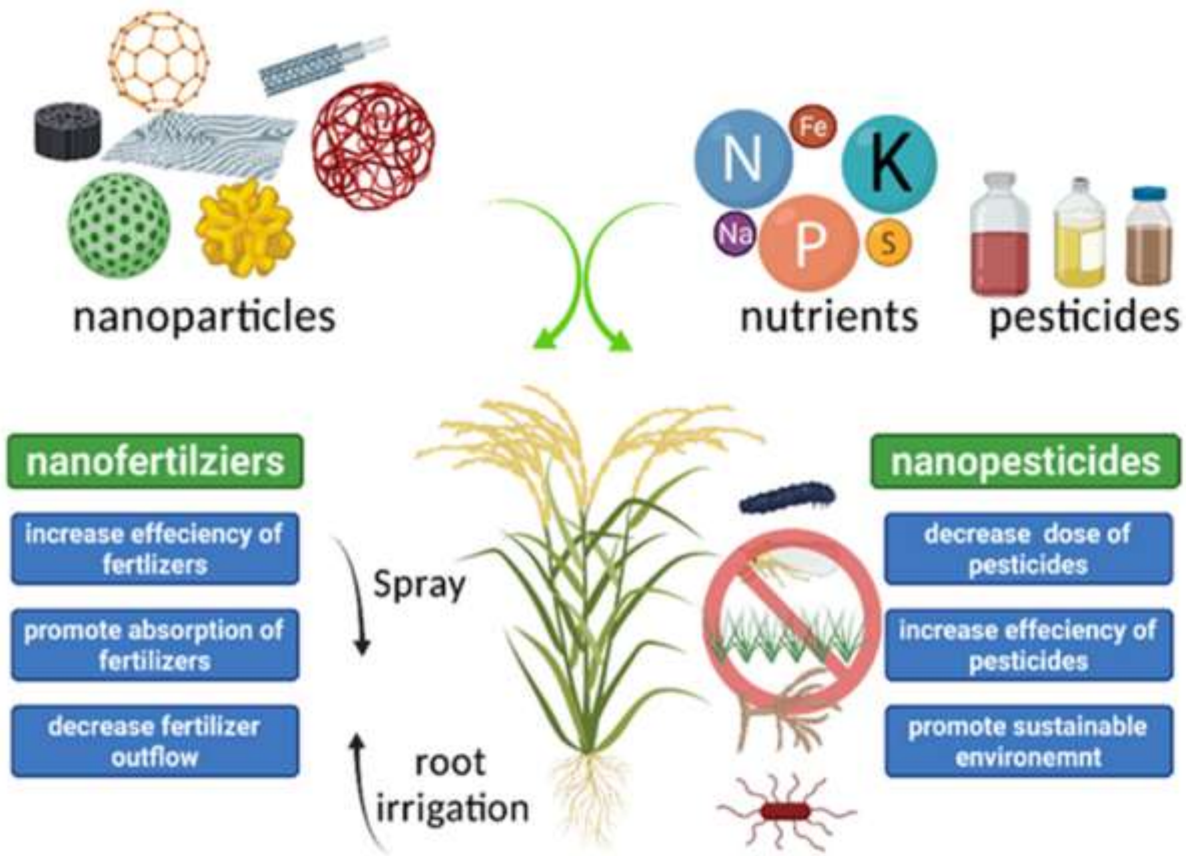

Figure 2: Simplified application model of nano fertilizers and nano pesticides

Micronutrients such as iron (Fe), boron (B), manganese (Mn), copper (Cu), zinc (Zn) and molybdenum (Mo) have also been enclosed in nanomaterials such as chitosan, zinc oxide NPs (ZnO NPs), Cu NPs and Ca nanoparticles, which improve the effective accessibility of micronutrients to plants [24]. These micronutrients play crucial roles in diverse plant physiological and chemical reactions, including photosynthesis, enzyme components and enzyme activators. Moreover, the application of nano fertilizers made of micronutrients promotes plant growth and increases yields. For example, ZnO NPs fertilization of strawberry significantly increased fruit setting and the grain yield compared to strawberry fertilized with zinc sulphate ($ZnSO_4$). As mentioned above, extra fertilizing micronutrients can enhance the photosynthesis rate and antioxidant enzyme activity. These physiological processes lead to elevated dry weights, shoot lengths, root lengths and biomass. Hence, foliar or drench application of nano type micronutrients significantly increases yields and promotes plant growth. The size distribution of NPs is an effective parameter related to fertilization efficiency [24]. Interestingly, nano type fertilizers all have decreased particles sizes and increased numbers of particles per unit, leading to high specific surface areas. Increased interaction with leaves and roots enables better absorption of fertilizers by plants. In addition, the unique properties of NPs lead to enduring effects. NPs encapsulated fertilizers resist degradation by hydrolysis, photolysis, evaporation, microbial organism decomposition and weathering. Furthermore, their porous structures and small size profiles may help NPs be transferred into cells by molecular transporters or ion channels, which activates sign alling pathways related to phytohormones or other growth factors [25]

2.2 Nano Pesticides

Nanomaterials can be used in pesticides to target pests more precisely. This means fewer chemicals are needed, which is better for the environment and for beneficial insects. Pesticides like herbicides, insecticides, bactericides, fungicides, and nematicides are commonly used to target weeds, pests, plant pathogens, nematodes, and microbes that are harmful to standing crops can be seen in Figure 3. Similar to nano fertilizers, nano pesticides have garnered significant interest in replacing conventional pesticides due to their effectiveness against various pests and opportunities for targeted action reducing possibilities of leakage to the environment. Coffee is one such constituent widely used world- wide gets affected by Collet otrichum causative agent of anthracnose. In a study, the effect of the ZnO nanoparticles on the causative agent of anthracnose is explored by exposing them to the fungus at different concentrations [26].

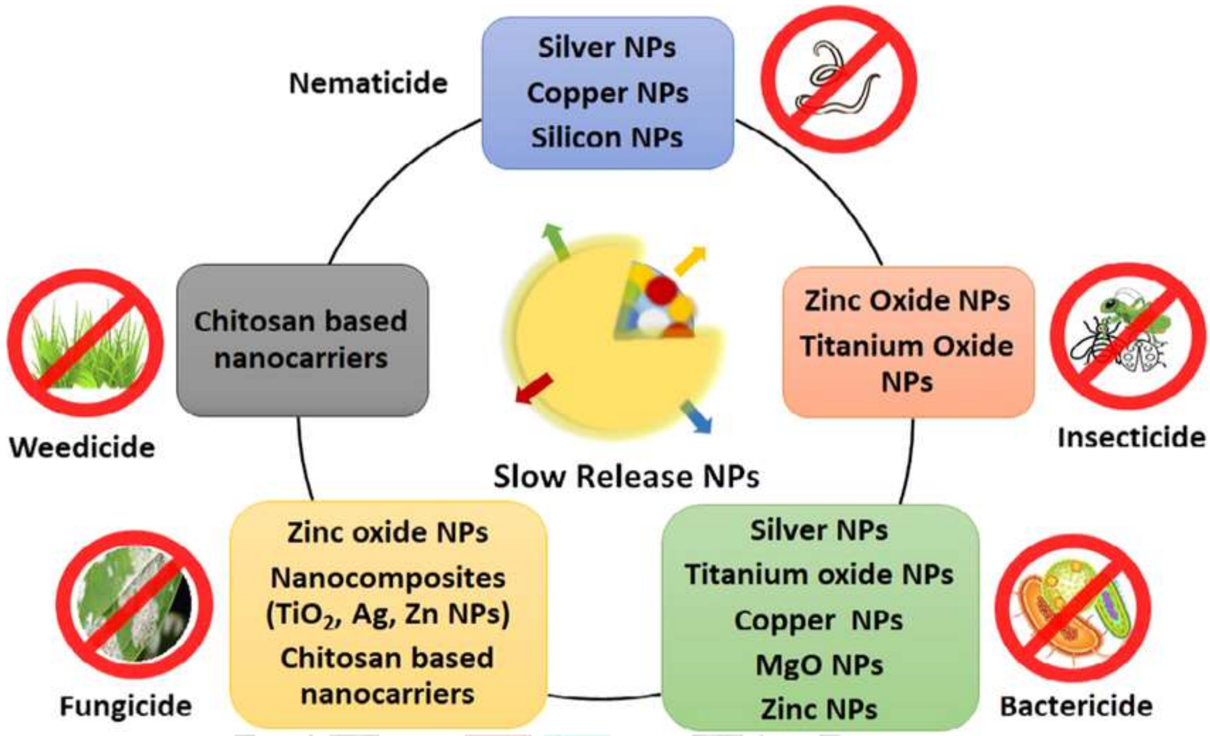

Figure 3: Different types of nanomaterials based nano pesticides in agriculture

In this study, cyproconazole is used as a positive control, and the fungus is grown as a negative control. The study concludes that the concentration of 15 mmol L-1 shows 96% fungal growth inhibition and formation of vacuoles-like structure and a decrease in cytoplasmic space. Simi- lar work has demonstrated the effect of ZnO nanoparticles synthesized via the chemical and green method (using garlic extract) on Mycenacitricolor and Colletotrichum sp., and concludes that the nano bio- hybrids show 97% and 93% growth inhibition of Mycenacitricolor and Colletotrichum sp. Respectively. Chitosan-based nanoparticles/nano formulations are extensively studied due to their biodegradability and biocompatibility. Zinc nanoparticles associated with chitosan strengthen plant immunity by increasing antioxidant and lignin content in maize crops to elevate disease control. Chitosan loaded with Spinosad and permethrin is checked for its antepasts activity at different concentrations using

3. Precision Farming with Nanotechnology

Nanotechnology significantly enhances precision farming by allowing targeted delivery of nutrients, pesticides, and herbicides, ensuring efficient utilization and reducing waste. Nano-sensors can monitor soil conditions, crop health, and environmental factors in real-time, allowing farmers to adjust inputs accordingly. Nanoparticles like nano-fertilizers can provide nutrients in a controlled manner, ensuring plants absorb them more effectively. Nanoparticles like nano-fertilizers can provide nutrients in a controlled manner, ensuring plants absorb them more effectively. Nano-sensors detect soil moisture, nutrient levels, pH, and even the presence of pathogens, which helps in timely intervention. Reduced use of fertilizers and pesticides helps lower the environmental impact and saves costs for farmers [27].

3.1. Enhancing Crop Protection and Pest Management

Nanotechnology offers innovative solutions for pest and disease management through nano-pesticides, nano-herbicides, and nano-fungicides**.** These nanomaterials are designed to provide slow and targeted release of active ingredients, which enhances the precision and effectiveness of pest control. By delivering these agrochemicals directly to the target area, nanotechnology reduces the amount needed, minimizing environmental contamination and lowering the risk of toxicity to non-target organisms [27]. This approach also ensures longer-lasting protection, improving the overall efficiency of pest and disease management in agriculture. Nano-pesticides offer significant advantages due to their increased solubility and stability**,** which make them more effective even at lower doses compared to conventional pesticides. The enhanced solubility ensures that the active ingredients are more easily absorbed and distributed within the target areas, while the increased stability prevents degradation over time. This allows for a more sustained and controlled release, reducing the frequency of applications and lowering the environmental impact, while still providing effective pest control. The encapsulation of active ingredients in nanomaterials provides a protective barrier that ensures prolonged action and significantly reduces degradation caused by environmental factors such as sunlight, temperature, and moisture. This controlled release mechanism allows the active ingredients to be delivered more effectively over time, enhancing their efficiency while minimizing the need for repeated applications [28]. As a result, nanomaterial-based formulations offer improved stability, reduced environmental impact, and more consistent pest and disease control in agricultural practices. These nano-based formulations enable the precise targeting of pests**,** ensuring that the active ingredients are delivered only to the intended organisms. This selective action significantly reduces the risk of harming non-target organisms, such as beneficial insects, wildlife, and soil microbes. By minimizing unintended exposure, these formulations lower the overall environmental hazard**s** associated with traditional pesticides, contributing to more sustainable and eco-friendly pest management practices [29].

3.2. Improving Soil Health and Fertility

That's a great insight! Nanotechnology can indeed play a significant role in sustainable agriculture. By using nanoparticles, fertilizers can be designed to release nutrients more slowly or target specific plants, thereby minimizing waste and improving nutrient use efficiency. Additionally, nanoparticles can help modify soil structure, enhance water retention, and promote beneficial microbial activity. The controlled release of nutrients from nano-fertilizers not only enhances plant uptake but also significantly reduces the environmental impact by minimizing nutrient leaching into groundwater. This precision in nutrient delivery can lead to more efficient use of fertilizers, promoting healthier crops while also protecting water quality. Nanoclay-based formulations can significantly enhance soil moisture retention, which is crucial in arid regions where water scarcity is a challenge. By improving the soil's physical properties, nano clays can create a more favorable environment for plant roots, helping to maintain moisture levels and promote better crop growth. That's an important benefit of nanomaterials in agriculture! By enhancing the growth of beneficial microorganisms, nanomaterials can positively impact soil structure and fertility. These microorganisms play a vital role in nutrient cycling, organic matter decomposition, and the formation of soil aggregates, which improve aeration and water retention [30]. Additionally, some nanomaterials can act as carriers for nutrients or bioactive compounds, further promoting microbial activity

3.3. Nanotechnology in Seed Science and Plant Breeding

Nano-coating seeds can indeed enhance their performance by providing essential nutrients and protective agents that improve germination rates and seedling vigor. This can lead to healthier plants that are better equipped to resist pests and diseases, ultimately contributing to higher crop yields. Nano-priming is a fascinating approach in agriculture that enhances seed performance by using nanoparticles to deliver essential nutrients, growth stimulants, or protective agents directly to the seeds. This method can improve germination rates, boost seedling Vigor, and increase overall crop yield while potentially reducing the need for chemical fertilizers and pesticides Nano-priming not only enhances uniform seedling emergence but also significantly improves a plant's ability to withstand various stresses, including pests, diseases, drought, and extreme temperatures. By providing targeted nutrition and protective agents, this technology helps strengthen the plants' defenses and overall resilience. Genetic engineering with nanocarriers is indeed transforming plant breeding by allowing for precise and efficient delivery of genes into plant cells. This method can enhance traits such as disease resistance, drought tolerance, and nutrient efficiency while minimizing off-target effects. The use of nanocarriers also improves the stability and bioavailability of genetic materials, making it a promising approach for developing improved crop varieties [31].

3.4. Water Management and Conservation

Nanotechnology indeed offers innovative solutions for water management in agriculture. Advanced filtration systems utilizing nanomaterials can effectively remove contaminants, ensuring clean water for irrigation. Additionally, nano-based water-retentive products, like hydrogels or nano clays, can improve soil moisture retention, reducing irrigation frequency and enhancing water use efficiency. Hydrogels can significantly improve water availability for crops by retaining moisture and releasing it gradually. This is particularly advantageous for promoting healthy plant growth, reducing the need for frequent irrigation, and minimizing water loss. By ensuring a consistent water supply, hydrogels can enhance crop resilience to drought and other water-related stresses, ultimately leading to better yields and resource efficiency. Nano-filters are indeed a powerful tool for improving water quality in agricultural settings. Their high surface area and tenable pore sizes enable them to effectively capture a wide range of contaminants, including pathogens, heavy metals, and organic pollutants. This ensures that the water used for irrigation is clean and safe, promoting healthier crops and reducing the risk of soil and water contamination. These filters can be integrated into existing irrigation systems or used in standalone setups, making them versatile solutions for addressing water quality issues. Smart irrigation systems using nano-sensors represent a significant advancement in agricultural water management. These sensors can provide real-time data on soil moisture levels, allowing for precise irrigation tailored to the needs of the plants. By monitoring moisture levels accurately, farmers can avoid overwatering, reducing water wastage and improving water efficiency. Additionally, these systems can be programmed to adjust irrigation schedules based on weather conditions and soil moisture data, further optimizing water use. This technology not only conserves water but also enhances crop health and yields [32].

3.5. Post-Harvest Management and Food Safety

Nanotechnology indeed plays a crucial role in enhancing food preservation and safety. Nano-packaging materials can provide barriers to oxygen, moisture, and light, which helps to extend the shelf life of agricultural products. These materials can also incorporate antimicrobial agents at the nanoscale to inhibit the growth of spoilage organisms, further preserving food quality. Additionally, nano-sensors can monitor the condition of the produce in real time, detecting changes in temperature, humidity, or gas composition, which can indicate spoilage or degradation. Nano-coatings can be applied to fruits and vegetables to create protective layers that maintain freshness and quality. Many nano-coatings incorporate antimicrobial agents that can inhibit the growth of bacteria and fungi, reducing spoilage and extending shelf life. Nano-packaging can include nanoparticles made from materials like silver, copper, zinc oxide, or natural extracts that exhibit antimicrobial properties. These agents can inhibit the growth of bacteria, Molds, and yeasts, which are responsible for spoilage. Many nano-packaging systems are designed to release antimicrobial agents in a controlled manner. This ensures that the active substances remain effective over a longer period, providing ongoing protection against microbial growth. Nano-packaging often enhances the barrier properties of traditional packaging by providing better protection against moisture, oxygen, and light, which can contribute to spoilage [33].

3.6. Enhancing Plant Disease Resistance

Nanotechnology indeed plays a crucial role in agriculture, particularly in disease management. Nano-biosensors can detect pathogens at very low concentrations, providing early warnings and enabling timely interventions [34]. These sensors can be designed to monitor specific pathogens, helping farmers take preventive measures before outbreaks occur. nanotechnology can enhance plant immunity by delivering beneficial compounds directly to the plant cells. For instance, nanoparticles can be used to transport bio stimulants or antimicrobial agents that boost a plant's natural defenses against diseases. This targeted approach not only improves efficacy but also reduces the need for chemical pesticides, making it a more sustainable option for crop protection. Nano-biosensors are highly sensitive tools that can detect pathogens at very low concentrations, often before symptoms appear. This early detection is crucial in agriculture for several reasons. By identifying the presence of pathogens early, farmers can implement control measures (such as targeted treatments or changes in management practices) before the disease spreads extensively. Early detection helps minimize potential crop damage and losses, ensuring healthier yields and more robust production. By using nano-biosensors, farmers can reduce the reliance on broad-spectrum pesticides, applying them only when necessary and in a targeted manner, promoting more sustainable agricultural practices. Nano-biosensors can be integrated into smart farming systems, providing real-time data that can be analysed to make informed decisions about crop management [35].

3.7. Enhancing Agricultural Productivity and Crop Yield

Nanotechnology enables the development of delivery systems that can transport agrochemicals (like fertilizers, pesticides, and herbicides) directly to the plant or soil where they are needed. This targeted approach minimizes wastage and maximizes the effectiveness of the applied substances. Nanomaterials can be engineered to release nutrients and agrochemicals slowly over time, matching the plant's needs. This controlled release reduces the risk of nutrient leaching into groundwater and ensures that plants receive a consistent supply of nutrients. Nanoparticles can improve the bioavailability of nutrients, making them easier for plants to absorb. For instance, nanoparticles can modify soil properties or facilitate the transport of essential nutrients into plant roots. Nanotechnology can help plants cope with abiotic stresses (such as drought or salinity) by enhancing nutrient availability and supporting overall plant health, which in turn contributes to better yields. By improving the efficiency of inputs, nanotechnology helps reduce the environmental impact of agriculture. Lower amounts of chemicals can lead to less runoff and pollution, making farming practices more sustainable. Nano-formulations allow for the targeted application of essential nutrients, hormones, and growth regulators [36]. This precision not only maximizes the efficacy of these inputs but also minimizes waste, leading to better crop growth and health. For example, nano-encapsulated fertilizers can ensure that nutrients are delivered directly to the root zone, where they are needed most.

4. Limitation

Just like every other technology, the nanotechnological means intended for an application in agriculture field suffers with advantageous and some drawbacks. Among different countries located around the world, only European Union and Switzerland incorporated nanoparticle specific provisions in legislation for agriculture. While non-EU countries are still indirectly dependent on the guidance of industries due to lack of nanoparticle specific provisions in their current legislations [33]. In the wake of fast-growing nanotechnology field and its application in this field, the unified policies and regulations regarding the synthesis of nanomaterials, use of nanomaterials, and their removal/elimination from the environment must be prepared and updated constantly as per the current state of the art nanotechnology. The practice of NPs in agriculture is still in the preliminary stage, and their full potency in agriculture is gradually transferring from the theoretical knowledge to the field application. For this, the researchers and industries face usual challenges, including high processing costs, standardizing the research protocols, concerns about public health and the environment, etc. Different methods of NPs application produce positive effects in plants. However, there is no accurate evidence that specific application method and specific type of NPs in agriculture is completely safe for plant and soil health.

Therefore, it is indeed necessary to explore these gaps in knowledge. In general, that smaller sized nanoparticles at lower concentrations improve the physiological/ biochemical status of plants under stress and nonstress conditions via seed priming & foliar spray methods only when used for a short duration. The use of nanoparticles for long duration and its impact on crop-associated food chain is not yet fully understood. Nanoparticles toxicity is a very important benchmark for transferring the technology from lab to field. To minimize the nanotoxicity, researchers have coated nanoparticles with different moieties, but, at present, no comprehensive report is available that covers both short-term and long-term effects of nanoparticles on crops and crop assisted food chain. These limitations should be covered in each study as the nanotoxicity study may vary depending on type of nanomaterial, crop species, and agricultural conditions. Special efforts can be driven to assess any possible resistance and defensive mechanism developed by plants to the action of these nanoparticles upon excessive or long-term usage. Soil fertility is another mission to be achieved while using NPs in agriculture because fertile soil contains all essential nutrients and millions of microbes that regulate plant growth in a healthy way. Therefore, soil health should be monitored for an extended duration after using these nanoparticles to ensure that it does not affect soil fertility regardless of the method of nanoparticles application. Despite all these concerns, nanoparticles serve as a novel and promising tool in the agricultural field.

CONCLUSION

Nanomaterials have the potential to significantly improve agricultural production by making fertilizers and pesticides more effective, enhancing soil health, and increasing crop yields. They offer benefits like controlled nutrient release, targeted pest management, and better soil properties, which can lead to more efficient and sustainable farming practices. However, there are challenges to consider, including potential environmental and health risks, high costs, and a lack of comprehensive regulations and long-term research. Addressing these challenges will be crucial for maximizing the benefits of nanomaterials in agriculture and ensuring their safe and effective use.

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