Nanotechnology for Enhanced Crop Production: A Brief Review

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Abstract- The field of nanotechnology has shown promise for enhancing agricultural output and solving the problems that plague contemporary agriculture. This review study examines how nanotechnology is used in agriculture and how it could improve agricultural output. It looks at a variety of nanomaterials and how they work, such as nanopesticides, nanosensors, nanofertilizers, and nanodelivery systems. The benefits, hazards, and mechanisms of action of using nanotechnology in agricultural production are all covered in the study. It also discusses the difficulties and potential outcomes of applying nanotechnology-based methods for sustainable agriculture. This comprehensive review delves into the advancements in nanotechnology and its potential applications in crop production. It provides insights into the use of nanomaterials, such as nanofertilizers, nanopesticides, and nanosensors, to improve nutrient uptake, enhance pest and disease control, and optimize resource utilization. Additionally, the review discusses the implications of nanotechnology on crop growth, stress tolerance, and yield, while addressing safety and regulatory considerations.

Index Terms- Nanotechnology, Nanomaterials, Crop, Agriculture, Nanosensor

I. INTRODUCTION

Nanotechnology is the control and manipulation of matter at the nanoscale, or between 1 and 100 nanometers. Materials have distinct physical, chemical, and biological characteristics that set them apart from their bulk counterparts at this size. Numerous industries, including medical, electronics, energy, and agriculture, can benefit greatly from nanotechnology.[1]

Potential Applications in Crop Production:

Due to its potential to completely alter crop production methods, nanotechnology has attracted a lot of interest in the agricultural industry. It is feasible to create creative solutions for boosting agricultural yield, resource utilisation, and environmental sustainability by using nanomaterials and nanodevices.[2] Some of the key potential applications of nanotechnology in crop production are:

1. **Nanofertilizers:** Designing and delivering fertilisers with controlled release mechanisms may be done using nanomaterials. Plants may more effectively absorb nutrients thanks to the use of nanofertilizers, which also minimise nutrient losses due to leaching and volatilization. They may also be programmed to release nutrients in response to changes in the environment, the demands of the plant, or certain growth phases.[3]
2. **Nanopesticides:** Formulations based on nanomaterials can improve the effectiveness of disease and pest management. Pesticides' stability, targeted distribution, and adherence to plant surfaces are all improved via nanoencapsulation. Nanopesticides can enhance the bioavailability of active chemicals, manage their release, and lessen their negative effects on the environment.[4]
3. **Nanosensors:** For monitoring plant health and environmental conditions, very sensitive and selective sensors may be created using nanotechnology. Nanosensors can identify changes in infections or toxins, pH, soil moisture, and nutrient levels. Nanosensor-based real-time monitoring enables farmers to manage resources more effectively, intervene quickly, and reduce losses.[5]
4. **Nanodelivery systems:** Nanotechnology facilitates the encapsulation and targeted delivery of bioactive compounds, such as plant growth regulators, beneficial microorganisms, and genetic materials. Nanodelivery systems protect these compounds, improve their stability, and enable their controlled release, ensuring efficient delivery to plant tissues and organs.[6]
5. **Precision agriculture:** Nanotechnology plays a crucial role in precision agriculture by providing tools for precise and localized application of agricultural inputs. Nanoscale devices can deliver nutrients, pesticides, or other treatments directly to specific plant tissues or root zones, optimizing resource utilization and minimizing wastage.[7]
6. **Soil and water remediation:** Contaminated soils and water sources can be cleaned up using nanomaterials., because consumption of contaminated water increased the burden of Typhoid fever.[123] Nanoparticles are a promising technique for environmental remediation since they may absorb, decompose, or immobilise contaminants from water and soil.[8]

Nanotechnology has a wide range of possible uses in crop production and holds considerable promise for overcoming the difficulties encountered by contemporary agriculture. However, given their potential effects on the environment and threats to human health, it is crucial to guarantee the appropriate and safe use of nanomaterials.[9]

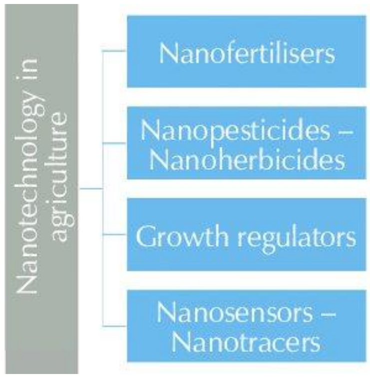

Figure 1 Nanotechnology in agriculture

Role of nanomaterials in enhancing nutrient uptake, efficiency, and delivery to plants:

In order to increase nutrient absorption, increase nutrient usage efficiency, and enable tailored nutrient delivery to plants, nanomaterials have shown to have considerable promise. These developments may help increase crop production and agricultural sustainability.[10] Here, we'll talk about how nanomaterials are used in various fields:

1. **Enhanced nutrient uptake:** Numerous processes exist through which nanomaterials can enhance the availability and absorption of nutrients by plants.[11]
    a. Increased surface area: Because of their high surface area to volume ratio, nanoparticles may interact and contact plant roots more readily. This more surface area makes it easier for nutrients to be absorbed and adsorb.[12]
    b. Root penetration: The absorption of nutrients from the soil solution is improved because nanoscale particles may more readily penetrate the root epidermis. This feature makes it possible for plants to absorb nutrients more effectively.[13]
    c. Stimulating root growth: Certain nanomaterials, including carbon-based nanoparticles or nanoscale biochar, can encourage root elongation and branching, which improves soil nutrient exploration and absorption.[14]
2. **Improved nutrient use efficiency:** Nanotechnology offers opportunities to enhance the efficiency of nutrient utilization by plants:
    a. Controlled-release fertilizers: The regulated and gradual release of nutrients over a long period of time is made possible by the use of nanomaterials to encapsulate fertilisers.[15] With this strategy, nutrients are delivered gradually, meeting the needs of the plant and minimising losses from leaching or runoff.[16]
    b. Nano-sized nutrient carriers: Nutrient carriers can be made of nanomaterials like hydrogels or nanoclays. They can improve nutrient stability and shield nutrients from environmental deterioration, enhancing their availability to plants.[17]
    c. Nutrient targeting: Targeting just particular plant organelles or tissues is possible using functionalized nanoparticles. Nanomaterials can increase nutrient utilisation efficiency and reduce losses by delivering nutrients directly to the required areas.[18]
3. **Targeted nutrient delivery:** Nanomaterials enable precise and targeted delivery of nutrients to plants:
    a. Foliar application: For foliar application, nanoparticles can be made into sprays or coatings. These mixtures can improve nutrient uptake through the leaf surface, giving the plant a direct source of nutrients.[19]
    b. Nanoscale delivery systems: Nutrients can be enclosed in nanocarriers like liposomes or polymeric nanoparticles to prevent their deterioration.[20] The tailored distribution of nutrients to plant tissues is ensured by these nanoscale delivery systems, which may be designed to release nutrients in response to certain triggers like pH, temperature, or enzyme activity.[21]
    c. Seed coating: Nutrient-rich seed coverings may be created using nanomaterials. These coatings give a concentrated supply of nutrients during the early phases of plant development and seed germination, assisting in the creation of healthy seedlings.[22]

More effective nutrient absorption, utilisation, and distribution are made possible in plants by using the special features of nanomaterials. To guarantee appropriate and sustainable use, it is crucial to carefully assess the safety, environmental effect, and regulatory issues related to the use of nanomaterials in agriculture.[23]

Nanoencapsulation of fertilizers for controlled release and targeted delivery:

A potential strategy for controlled release and targeted nutrient delivery to plants is the nanoencapsulation of fertilisers. This method, which has various advantages for agricultural applications, involves encapsulating fertiliser molecules inside nanoscale structures.[24] Here, we will discuss the advantages and mechanisms of nanoencapsulation for controlled release and targeted delivery of fertilizers:

1. Controlled release of nutrients: The exact control of nutrient release kinetics made possible by nanoencapsulation guarantees a steady and regulated supply of nutrients to plants.[25] By coordinating the nutrient release with the plant's development phases and needs, this regulated release helps to prevent nutrient losses due to leaching or volatilization.[26] Some mechanisms involved in controlled release include:
    a. Diffusion-controlled release: By diffusing through the nanoparticle matrix, the encapsulated nutrients are gradually released, giving plants a steady and continual supply of nutrients.[27]
    b. pH-responsive release: It is possible to programme nanoparticles to react to pH changes. This maximises nutrient availability by enabling nutrient release in certain pH environments, such as those present in the rhizosphere or in particular plant organs.[28]
    c. Environmental-triggered release: The release of nutrients from the nanocarriers may be triggered by environmental factors like temperature, moisture, or enzymes, guaranteeing that they are released when and where the plant needs them.[29]
2. Protection and stability of nutrients: By creating a layer of defence around the encapsulated nutrients,

nanoencapsulation increases their stability and protects them from environmental deterioration.[30] This defence ensures that the nutrients are still accessible for plant absorption by preventing nutrient loss through microbial decay, volatilization, or chemical reactions.[31]

3. Targeted delivery to plant roots: Nutrient efficiency is increased and waste is decreased when nutrients are delivered specifically to a plant's root zones through nanoencapsulation.[32] In order to provide direct nutrient availability to plants, the encapsulated nutrients might be created to attach to root surfaces or penetrate into the root tissues.[33] Some approaches for targeted delivery include:

a. Surface functionalization: Functional groups that encourage root surface adherence can be added to nanoparticles to provide localised nutrient delivery.[34]

b. Root penetration: The root epidermis can be more efficiently penetrated by nanoscale particles, enabling direct nutrition supply to the interior root tissues where nutrient absorption occurs.[35]

c. Mycorrhizal association: Nutrients may be given to mycorrhizal fungi, which live in symbiotic relationships with plant roots, via nanoencapsulation.[36] The efficiency of nutrient absorption is increased when the fungus absorb the encapsulated nutrients and deliver them to the plant.[37]

A flexible and effective method to increase nutrient availability, minimise losses, and maximise nutrient utilisation in crop production is fertiliser nanoencapsulation. When developing and applying nanoencapsulation techniques in agricultural systems, it is essential to take into account aspects like the toxicity of nanoparticles, their influence on the environment, and their cost-effectiveness.[38]

Impact of nanofertilizers on nutrient use efficiency, plant growth, and yield:

Nanofertilizers have demonstrated considerable promise for optimising the effectiveness of nutrient utilisation, promoting plant development, and eventually raising agricultural output.[39] Numerous advantages in agricultural applications are provided by their special qualities and controlled-release methods.[40] Here, we will discuss the impact of nanofertilizers on nutrient use efficiency, plant growth, and yield:

1. Improved nutrient use efficiency

- Controlled release: In order to fit the plant's nutritional requirements, nanofertilizers can release nutrients gradually and under regulated conditions.[41] This regulated release makes sure that nutrients are accessible to plants for a long time and reduces nutrient losses due to leaching or volatilization.[42]

- Enhanced nutrient uptake: Because of their high surface area to volume ratio, nanoparticles can make more direct touch with plant roots. This expanded surface area makes it easier for plant roots to better adsorb and absorb nutrients, increasing the effectiveness of nutrient intake.[43]

- Targeted delivery: To maximise nutrient uptake, nanofertilizers can be made to distribute nutrients specifically to particular plant tissues or root zones. By providing nutrients where they are most required, this tailored distribution guarantees that they are used efficiently overall.[44]

2. Enhanced plant growth:

- Nutrient availability: In order for plants to grow and develop, steady and continuous nutrient supply is provided by nanofertilizers.[45] Since nutrients are consistently available throughout the plant's growth stages thanks to the controlled-release capabilities of nanofertilizers, healthy and strong plant growth is encouraged.[46]

- Increased nutrient bioavailability: Nutrient solubility and bioavailability can be improved by using nanofertilizers.[47] Poorly soluble nutrients can dissolve more quickly thanks to nanoparticles, making them more available to plants. This enhanced nutrient bioavailability aids in better plant development and growth.[48]

3. Increased crop yield:

- Nutrient optimization: Nanofertilizers' controlled-release properties make sure that plants receive the optimum amount and timing of nutrients.[49] The delivery of nutrients is optimised, which improves crop production and output.[50]

- Stress tolerance: Plants' ability to withstand stress has been demonstrated to be improved by several nanofertilizers.[51] They can assist plants in overcoming a variety of abiotic stressors, such as salt, drought, or heavy metal toxicity, minimising yield losses in arid environments.[52]

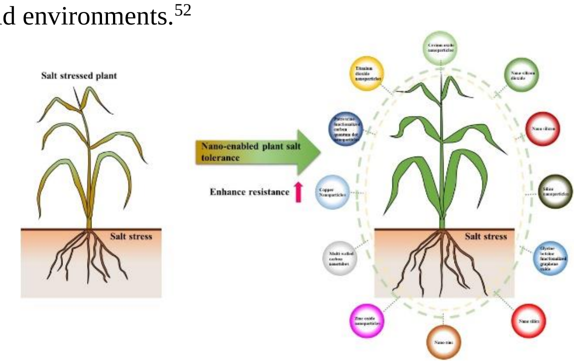

Figure 2: Stress Tolerance of Crops with Nanomaterial Treatment

- Yield-enhancing additives: To increase the potency of nanofertilizers even further, chemicals like plant growth regulators or advantageous microorganisms can be included into their formulation.[53] Together, these chemicals can boost output, nutrient absorption, and plant development.

It is important to note that the effects of nanofertilizers on the efficiency of nutrient consumption, plant development, and production might differ depending on factors including crop species, soil conditions, treatment rates, and the particular nanomaterial utilised.[54] To guarantee that nanofertilizers are used safely and sustainably in agriculture, it is also necessary to properly evaluate the long-term environmental consequences and any hazards connected with them.[55]

Nanopesticides for effective disease and pest management

Effective control of pests and diseases while reducing the environmental effect of conventional pesticide use is possible with the help of nanomaterial-based techniques. The use of nanoparticles as carriers for the precise delivery of pesticides in nanopesticides has demonstrated improved effectiveness and decreased environmental dangers.[56] An overview of nanomaterial-based methods, nanoparticle carriers, and the advantages of nanopesticides may be found below:

Nanomaterial-based approaches for pest and disease management:

Nanoparticles as active agents: Nanoparticles can naturally possess pesticidal characteristics. Some nanoparticles, including silver nanoparticles, are effective against a variety of plant infections because they have antibacterial and antifungal capabilities.[57]

Pesticide encapsulation: Pesticides may be contained within nanoscale structures like lipid-based vesicles or polymeric nanoparticles.[58] The active substances are shielded from deterioration by this encapsulation, which also increases their stability and increases their effectiveness against pathogens and pests.[59]

Nanoparticles as carriers for targeted delivery of pesticides:

Systems for controlled release: Nanocarriers enable the controlled release of pesticides, resulting in a continuous and protracted release of active components. This controlled release technique boosts the pesticide's effectiveness and endurance, requiring fewer treatments overall.[60]

Delivery that is particularly targeted: Nanocarriers can be functionalized to target pests, diseases, or damaged plant tissues.[61] By attaching to pest surfaces or penetrating their cuticles, functionalized nanoparticles can deliver pesticides directly to the target species while minimising exposure to unintended targets.[62]

Enhancers of adhesion and penetration: Nanoparticles can increase the retention and discharge of pesticides by increasing their adherence to plant surfaces. Additionally, they can make it easier for insecticides to penetrate plant cuticles or pest exoskeletons, increasing their effectiveness against pests and illnesses.[63]

Enhanced efficacy and reduced environmental impact of nanopesticides:

Increased bioavailability: Nanopesticides increase the active chemicals' bioavailability and solubility, which increases the pests' or diseases' capacity to absorb them and use them effectively.[64] The increased bioavailability increases the pesticide's effectiveness while lowering the necessary application rates.[66]

Reduced environmental contamination: By limiting the quantity of active chemicals released into the environment, nanopesticides can reduce environmental contamination.[67 68] A more focused and effective application is produced by the targeted delivery and controlled-release mechanisms, which also reduce pesticide runoff, leaching, and drift.[69]

Reduced development of resistance: Nanopesticides' targeted and controlled-release properties can assist reduce the emergence of resistance in pests and illnesses.[70] The chance of pests acquiring resistance to the active components is reduced by providing pesticides in a more targeted and consistent manner.[71]

Nanopesticides provide the possibility of effective disease and pest management with little negative environmental effects. To analyse the possible dangers connected to nanomaterials and nanopesticides, particularly their persistence in the environment and their impact on creatures other than the targets, further study must be done. The safe and long-lasting application of nanopesticides in agriculture depends on responsible usage, regulation, and accurate risk assessment.[72 73 74 80]

Nanosensors for real-time monitoring of plant health

Nanosensors provide creative ways to monitor plant health in real time, enabling accurate and timely crop management practises. They use nanotechnology to create very sensitive and focused sensors that can identify different plant factors.[75 76 79] Here, we'll talk about the uses of nanobiosensors in precision agriculture, the use of nanotechnology in the creation of sensors for tracking plant health, and the potential advantages of nanosensors for improving resource usage and crop management.[78]

Use of nanotechnology in the development of sensors for monitoring plant health:

Monitoring of nutritional status: Nanosensors are able to identify and quantify the concentration of vital nutrients in soil or plant tissues, giving real-time data on nutrient availability. They make it possible to precisely monitor nutrient surpluses or deficits, assisting farmers in adjusting fertilisation plans accordingly and maximising nutrient management.[81 85]

Assessment of water accessibility: Nanosensors can evaluate soil moisture content, enabling farmers to keep an eye on water accessibility and make wise irrigation decisions.[83 86] They offer precise, localised data on the soil moisture content, assisting in the planning of irrigation systems and avoiding plant water stress.[82 84]

Monitoring of the stress response: Nanosensors are capable of detecting and keeping track of certain stress-related characteristics, such as reactive oxygen species (ROS) or hormonal alterations, which can provide plants early warning signs of stress. This helps farmers to prevent stressful situations from occurring and reduce crop losses by taking proactive actions.[86]

Nanobiosensors and their applications in precision agriculture:

Pathogen and disease detection: Nanobiosensors have the ability to instantly identify the presence of bacterial, viral, or fungal plant pathogens. They have excellent specificity and sensitivity, making it possible to diagnose diseases early and take quick action to control them. Precision disease control tactics may be implemented with the use of nanobiosensors, reducing the need for broad-spectrum insecticides.[87]

Plant metabolite monitoring: Nanobiosensors are able to assess particular metabolites or biomarkers related to the growth, development, and stress responses of plants. With the use of these insights on the physiological status of plants, specific treatments and specialised crop management techniques may be carried out.[88]

Environmental evaluation: In the presence of plants, nanobiosensors can keep an eye on environmental variables including temperature, humidity, light intensity, and air quality.[89] These sensors aid farmers in understanding how microclimates impact plant development and Potential benefits of nanosensors in optimizing resource utilization and crop management:

Application of resources with precision is made possible by nanosensors, which allow for localised and accurate monitoring of plant characteristics.[90] Based on real-time data, farmers may modify the rates at which they apply fertiliser, the timing of their irrigation systems, or their pest control plans, maximising resource efficiency and reducing waste.[91]

Improvement in decision-making Farmers may receive precise and fast information on plant health and environmental factors through real-time monitoring using nanosensors.[92 93 95] With this knowledge, farmers are better equipped to choose crop management strategies that will increase production, lower input costs, and promote more sustainable farming.

Better crop quality and yield potential: Nanosensors help sustain ideal growth conditions, which boost crop quality and yield potential by continually monitoring plant health and quickly responding to stress circumstances.[94]

By enabling real-time monitoring capabilities for plant health, nutritional status, water availability, and stress responses, nanosensors hold tremendous promise for precision agriculture. They make it possible for more informed, data-driven decisions, which optimise resource use, lessen negative environmental effects, and boost agricultural output. To guarantee the dependability, scalability, and affordability of nanosensors for wide-scale application in agricultural systems, more research and development are necessary.[96]

Nanodelivery systems for controlled release of bioactive compounds

For the efficient encapsulation and delivery of bioactive substances, such as plant growth regulators (PGRs) and advantageous microorganisms in agriculture, nanodelivery systems are used. The stability, controlled release, and targeted distribution of these bioactive chemicals are all significantly enhanced by nanotechnology.[97 98 99 101] The benefits of nanoparticles in controlled release, the function of nanotechnology in encapsulating and delivering bioactive substances, and the consequences for crop development, yield, and stress tolerance are all covered in this article:

Role of nanotechnology in encapsulating and delivering bioactive compounds:

Encapsulation of bioactive substances: Nanomaterials with shapes resembling nanoparticles or nanocapsules can contain bioactive substances.[100] The substances are shielded from oxidation, their stability is increased, and their bioavailability is increased by this encapsulation.

Nanoparticles may be loaded precisely with bioactive substances, allowing for regulated dosage.[103 104] Bioactive ingredient loading and targeting. In order to ensure that the bioactive substances are delivered to certain plant tissues, cells, or organelles, functionalizing nanoparticles enables targeted distribution and showing the exact mechanisms and inhibitory effect of different natural compounds.[75 100 101 102]

Nanomaterials for enhanced stability, controlled release, and targeted delivery of bioactive compounds:

A greater degree of stability is achieved by encapsulation in nanoparticles, which offers defence against environmental variables including pH, temperature, and enzymatic destruction. This stability keeps bioactive chemicals from prematurely degrading or losing their potency, preserving their effectiveness over time.[105]

Controlled release: Nanomaterials have the ability to release bioactive substances over a sustained period of time.[106] This controlled release reduces the number of times it is applied and maximises resource use by matching the timing and duration needed for the best biological effects.[107]

Targeted delivery: Using nanomaterials, bioactive substances may be delivered precisely to the specified target region, such as plant roots or certain plant tissues. This focused distribution increases the chemicals' bioavailability and guarantees that they have the greatest possible effect on the intended location.[108]

Implications for crop growth, yield, and stress tolerance:

Controlled release of PGRs through the use of nanodelivery technologies enables the exact management of plant growth and development. By enhancing favourable features like greater branching, root growth, blooming, or fruit set, this control can raise agricultural production and output.[109]

Improved stress tolerance: Plants in harsh conditions may receive substances that reduce stress, such as antioxidants or osmoprotectants, through nanodelivery systems. By boosting stress tolerance and reducing yield losses, this tailored delivery aids plants in better coping with abiotic challenges like drought, salt, or severe temperatures.[110]

Nanodelivery devices can successfully transfer beneficial microorganisms, such as bacteria that promote plant development or mycorrhizal fungus, to plant roots for biocontrol and nutrition augmentation. These advantageous microbes can increase nutrient intake, boost soil health, provide disease resistance, and encourage.[111]

To boost crop development, yield, and stress tolerance, nanodelivery devices provide considerable benefits in the regulated release and targeted delivery of bioactive substances.[112] To ensure their responsible usage in agriculture, however, it is crucial to guarantee the safety, effectiveness, and regulatory compliance of nanomaterial-based delivery systems.[113]

Potential risks associated with nanotechnology in agriculture

Although there are many advantages to using nanotechnology in agriculture, it is important to weigh the dangers and assure responsible use via safety evaluations and regulations. Here, we'll talk about the possible dangers of using nanotechnology in agriculture, the value of safety reviews and laws governing the use of nanomaterials in crop production, and the relevance of risk management.[114]

Potential risks associated with nanotechnology in agriculture:

Environmental impact: Ecosystems and non-target creatures may be adversely affected by nanomaterials.[116] They may affect ecological processes or harm beneficial creatures if they build up in soil, water, or plant tissues.[117]

Human health issues: If some nanomaterials are swallowed, breathed, or come into touch with the skin, they may endanger human health. It is crucial to comprehend the possible toxicity and long-term repercussions of nanomaterial exposure.

Unknown ecological and health effects: Because nanotechnology is so new, there may be questions and knowledge gaps about the environmental and health effects of using nanomaterials in agriculture.[115]

Safety assessments and regulations for nanomaterials in crop production:

Risk assessment: Thorough safety analyses should be carried out to weigh the advantages and dangers of using nanomaterials in agriculture. Assessing their toxicity, persistence, environmental destiny, and potential for bioaccumulation is necessary for this.

Regulatory frameworks: In creating policies and requirements for the safe application of nanomaterials in agriculture, regulatory organisations are essential. These frameworks make sure that environmental protection and safety standards are met during the development and implementation of nanomaterials.[116]

Labelling and openness: The ability to make educated decisions and successfully control possible dangers is provided to farmers, consumers, and regulatory agencies through clear labelling and accurate information regarding goods made from nanomaterials.[117]

Importance of responsible use and risk management:

Risk reduction: In order to employ nanotechnology in agriculture responsibly, precautions must be taken to reduce possible risks.

This may involve proper handling, application techniques, and waste disposal methods.

Systems of ongoing monitoring and surveillance are essential for determining how nanomaterials used in agriculture may affect the environment and human health. Early diagnosis of any negative consequences can lead to fast risk management techniques.[118]

Education and information: It is crucial to educate all relevant parties—farmers, scientists, politicians, and the general public—about the advantages and possible hazards of nanotechnology in agriculture. Education facilitates the adoption of suitable risk management practises and helps to encourage responsible use.

In conclusion, even though nanotechnology has enormous promise for agriculture, it is crucial to address any dangers through safety reviews, laws, responsible use, and risk management techniques. We can maximise the advantages of nanotechnology while minimising any negative consequences on the environment, human health, and ecosystems by guaranteeing the safe and responsible deployment of nanomaterials.[119]

Future prospects and challenges

Although there are promising possibilities for the use of nanotechnology in agricultural production, there are also issues that must be resolved. Here, we'll talk about the latest developments and next directions in nanotechnology for crop production, as well as how it integrates with other recent developments and the difficulties of scalability, cost-effectiveness, and public acceptance:

Emerging trends and future directions in nanotechnology for crop production:

Nanoscale precision agriculture: By combining nanosensors, nanofertilizers, and nanopesticides with precision agricultural methods, it is possible to increase crop yield and sustainability through real-time monitoring, tailored input delivery, and resource efficiency.

Smart nanomaterials: The creation of responsive smart nanoparticles with stimuli-triggered release or sensing capabilities would improve crop management's functioning and control.

Nanotechnology can revolutionise molecular breeding and genetic engineering by providing precise delivery of genetic materials, gene editing tools, and gene expression regulators to improve agricultural attributes. Nanogenomics and molecular delivery are two such areas.

Nanomaterials can aid in the construction of efficient plant-microbe systems for better nutrient absorption, disease resistance, and stress tolerance in crops. Nanobiosystems for plant-microbe interactions.[120]

Integration of nanotechnology with other emerging technologies:

Biotechnology: Combining nanotechnology with biotechnology techniques like genetic engineering or gene editing can increase the effectiveness of targeted gene delivery, altering gene expression, and creating crops that have been genetically engineered to have better features.

Precision agriculture: Nanosensors, nanofertilizers, and nanopesticides may be coupled with remote sensing, GIS, and data analytics technologies to provide site-specific management and customised crop care for the most efficient use of resources and sustainability.[121]

Challenges in scalability, cost-effectiveness, and public acceptance:

Scalability: There are issues with production, manufacturing, and application methods when scaling up nanotechnology-based solutions from small-scale agricultural settings. It necessitates resolving concerns including price, scalability, and compatibility with already-used agricultural methods.

Cost-effectiveness: To ensure cost-effectiveness and viability for wide-scale adoption by farmers, the cost of nanomaterials, production, and application methodologies must be taken into account.

Societal acceptability and laws: It is crucial that the general public understands, accepts, and uses nanotechnology in agriculture. To address possible issues and guarantee the responsible use of nanomaterials in agriculture, open communication, unambiguous labelling, and well-defined rules are required.[122]

Collaboration between scientists, politicians, industry stakeholders, and the general public is necessary to address these difficulties. Unlocking the full potential of nanotechnology in agriculture will help to improve global food security and sustainable agricultural practises. This will be accomplished through continued research, development, and investment in nanotechnology for crop production, as well as thorough risk assessments and regulatory frameworks.[123]

II. CONCLUSION

In conclusion, nanotechnology presents important chances to improve crop output and deal with issues facing contemporary agriculture. Numerous elements of crop production, including nutrient absorption, efficiency, and delivery; pest and disease management; real-time monitoring of plant health; and regulated release of bioactive chemicals, can be enhanced by the use of nanomaterials. The main conclusions and results of nanotechnology for improved agricultural production are as follows:

Nanomaterials promote nutrient management and plant development by improving nutrient absorption, efficiency, and delivery. Sustainable agricultural practises are promoted by nanopesticides, which effectively manage pests and diseases while having no negative environmental impact. Nanosensors make it possible to monitor plant health in real-time, enabling prompt intervention and precision crop management. By ensuring regulated release of bioactive chemicals, nanodelivery systems optimise resource use and enhance crop growth, yield, and stress tolerance. The application of nanotechnology in agriculture must, however, take safety and legal factors into account. It is necessary to address potential concerns related to nanoparticles through safety evaluations, laws, responsible usage, and risk management techniques. More study and cooperation are required to fully realise the promise of nanotechnology in sustainable agriculture. Continued efforts should concentrate on affordability, acceptability among the general public, and scalability. The advantages of nanotechnology in agricultural production can be increased by combining it with other cutting-edge technologies, such as biotechnology and precision farming. We can create the conditions for sustainable agriculture, increased crop yield, and increased food security throughout the world by using the promise of nanotechnology and tackling its problems. In order to fully realise the promise of nanotechnology for the benefit of agriculture and society as a whole, further research, collaboration, and appropriate application will be essential.

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