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NANOTECH HARVEST: FOSTERING WELLNESS IN SUSTAINABLE FARMING

Editors
Shweta Sharma
Dilbag Singh
Jeevan Jyoti
Sandeep Gawdiya

Bhumi Publishing, India
First Edition: 2024

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PREFACE

In an era where the convergence of technology and agriculture has become paramount, the role of nanotechnology in fostering sustainable farming practices has never been more critical. It is with great enthusiasm and a deep sense of responsibility that we present "Nanotech Harvest: Fostering Wellness in Sustainable Farming."

This book aims to bridge the gap between advanced scientific research and practical agricultural applications, highlighting how nanotechnology can revolutionize sustainable farming practices. As we navigate the challenges of a growing global population and the need for efficient, eco-friendly agricultural methods, the integration of nanotechnology offers promising solutions that can significantly impact both productivity and environmental stewardship.

Our journey in compiling this book has been one of discovery and collaboration. We have sought to gather and present cutting-edge research, innovative applications, and practical insights that reflect the latest advancements in the field. From enhancing soil health and optimizing nutrient delivery to developing eco-friendly pest control methods, the potential applications of nanotechnology in agriculture are vast and transformative.

The contributions of numerous experts, researchers, and practitioners have made this book possible. Their dedication to advancing the field and their commitment to fostering sustainable practices are evident in the comprehensive and insightful chapters that follow. We are particularly grateful for their collaboration and for sharing their expertise with a wider audience.

We also recognize the importance of making this knowledge accessible to a diverse readership. Whether you are an academic, a practitioner, or simply a curious learner, we hope this book serves as a valuable resource, offering both foundational knowledge and practical applications.

As editors, we have endeavored to ensure that this book not only presents the latest research but also inspires innovation and encourages further exploration in the field of nanotechnology and sustainable farming. Our goal is to foster a greater understanding of how these technologies can be harnessed to address some of the most pressing challenges in agriculture today.

We extend our sincere thanks to all those who have supported us in this endeavor, and we hope that "Nanotech Harvest: Fostering Wellness in Sustainable Farming" will contribute to a more sustainable and prosperous future for agriculture worldwide.

Editors

ACKNOWLEDGEMENTS

We wish to extend our deepest gratitude to all those who have supported us in the creation of "Nanotech Harvest: Fostering Wellness in Sustainable Farming."

Our heartfelt thanks go to our mentors, whose expert guidance and encouragement have been instrumental in shaping the development and success of this book. Their invaluable insights and steadfast support have been a cornerstone throughout this journey.

We are profoundly grateful to the authors, editors, and reviewers who contributed their time and expertise to ensure the accuracy and clarity of the content. Their constructive feedback and thoughtful suggestions have significantly enhanced the quality of this book.

We also wish to acknowledge the dedicated staff and librarians at CCS HAU, Hisar, and IARI, Delhi. Their assistance in acquiring relevant resources and providing access to essential materials was crucial to the completion of this book.

A special note of appreciation goes to our families and friends, whose belief in us and constant motivation have been a source of strength throughout the writing process. Their unwavering support and understanding have been invaluable.

Finally, we extend our sincere thanks to the readers and learners who will engage with this book. Your curiosity and enthusiasm for nanosciences are the driving force behind this project. We hope this book serves as a valuable and accessible resource for your academic and personal endeavors.

Thank you once again to everyone who has played a role in this book’s development. Your support has been indispensable, and we are deeply appreciative of your contribution to this journey.

Editors

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NANOTECHNOLOGY FOR ENHANCED NUTRIENT DELIVERY IN AGRICULTURE

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Abstract:

Nanoparticles can be used as carriers for delivering nutrients to plants, improving their absorption and utilization. By encapsulating nutrients within nanoparticles their stability can be increased, reducing nutrient losses due to volatilization or leaching. Furthermore, nanoparticles can be functionalized to release nutrients in a controlled manner, ensuring optimal nutrient availability for plants. This can lead to improved crop yields, reduced fertilizer use and minimized environmental impacts. These nano-fertilizers would be able to trigger plant capabilities, take advantage of nutrients and amenities in the rhizosphere that were not previously accessible, and be delivered in real-time to either soil or via foliar applications. These modern delivery platforms are used to improve the bioavailability of nutrients, increase productivity of agriculture in a sustainable manner and to the extent possible minimize environmental damage by reducing the need to overuse fertilizers. The use of nano-technologies in the nutrient management system for agricultural ecosystems is well grounded and provides great promise to enhance the productivity, the quality and the adequation of crops to face an increasingly demanding agricultural sector, providing food security and sustainability of agricultural development globally. In this chapter, we explore the applications of nanotechnology in enhancing nutrient delivery in agriculture. We discuss the potential benefits of using nanoparticles as carriers for delivering nutrients to plants, and how this can lead to improved crop yields and reduced environmental impacts.

Keywords: Agricultural, Ecosystems, sustainability, Nanotechnology, Nutrient delivery

Introduction:

Nanotechnology has emerged as a promising field with potential applications in various industries, including agriculture (Patel & Munjal, 2022). The challenge of ensuring global food security is intensifying as the world population is expected to reach nearly 10 billion by 2050. Agriculture will need to make changes to meet the demands of these consumers for agriculture products with new seeds, better and more environmentally friendly agro-chemicals and more nutritional value in the products. It offers the opportunity to revolutionize the way we deliver nutrients to plants and improve crop yields. By incorporating nanotechnology into agriculture, we can enhance the efficiency and effectiveness of nutrient delivery, ultimately leading to increased crop yields and improved food production (Zhao *et al.*, 2020). This chapter aims to provide an overview of the current research and developments in the use of nanotechnology for enhanced nutrient delivery in agriculture (Patel & Munjal, 2022). Key advancements and opportunities in hydroponics have paved the way for more efficient and sustainable methods of agricultural production.

Nanotechnology is also thought to have the ability to totally change how nutrients can be delivered to crops. Nanotechnology is the manipulation of materials at a scale of 1 to 100 (nanometer) with interesting behaviors and functions that do not exist Properties of traditionally used materials. Nano-fertilizers: An innovative way of Nano-fertilizers represents a breakthrough in integrated nutrient management in agriculture. Their development of this nano-fertilizer is expected to achieve unprecedented levels of precision and efficiency in delivering essential nutrients to plants. Nano-fertilizers boost plant growth and productivity by activating plant traits and enhancing nutrient use efficiency. Nanotechnology holds immense potential in the field of agriculture as it can revolutionize nutrient delivery and enhance crop yields. Nano-fertilizers also have broader advantages beyond the scope of nutrient delivery. They can release funds from nutrients which were already accessible in the rhizosphere and have the potential to release ones that were previously unavailable to plants and can be applied to the soil or leaf in real time/metaanalysis. In the last 15 years, major developments have been made in this area which led to four types of nano-fertilizers (i) macronutrient nanofertilizers, (ii) micronutrient nanofertilizers, (iii) nanomaterial-enhanced fertilizers, and (iv) Plant growth-stimulating nanomaterials. In recent years, nanotechnology has emerged as a promising tool for enhancing nutrient delivery in agriculture (Kharisov *et al.*, 2013). These advancements in nanotechnology have opened up new possibilities for improving nutrient uptake and utilization in plants, ultimately leading to increased crop productivity and sustainability (Patel & Munjal, 2022). The incorporation of nanotechnology in agriculture has led to significant advancements in nutrient delivery. These advancements include the development of nano-fertilizers that provide improved delivery of macronutrients and micronutrients, as well as nanomaterial-enhanced fertilizers that have the ability to release nutrients slowly over time. In addition, nanotechnology has also facilitated the development of plant growth-stimulating nanomaterials that can enhance plant growth by promoting nutrient absorption and metabolic activities. The use of nanotechnology in agriculture has revolutionized nutrient delivery by introducing four types of nano-fertilizers: macronutrient nanofertilizers, micronutrient nanofertilizers, nanomaterial-enhanced fertilizers, and plant growth-stimulating nanomaterials.

(i) Macronutrient nanofertilizers: Macronutrient nanofertilizers are a type of nanofertilizer that is specifically designed to deliver essential macronutrients to plants in a more efficient and targeted manner. These nanofertilizers are formulated with nanoparticles that can encapsulate macronutrients such as nitrogen, phosphorus, and potassium. These nanoparticles facilitate the controlled release of macronutrients, ensuring that plants receive a steady and optimal supply (Kharisov *et al.*, 2013). This steady and optimal supply of macronutrients is crucial for ensuring healthy plant growth and maximum crop productivity (Suddin *et al.*, 2021).

(ii) Micronutrient nanofertilizers: Micronutrient nanofertilizers, on the other hand, are nano-fertilizers that are specifically designed to deliver essential micronutrients to plants. These nano-fertilizers are formulated with nanoparticles that can encapsulate micronutrients such as iron, zinc, and manganese (Patel & Munjal, 2022).

The need for improved nutrient delivery

In the global quest for improved health and well-being, there is a growing recognition of the need for improved nutrient delivery. This recognition comes from the understanding that the nutritional state of an organism plays a crucial role in its overall health and functioning (Shik & Dussutour, 2020). Mineral nutrient deficiencies are an important limitation to crop growth and productivity. Degradation, erosion and salinization of the soils have further resulted in deficiency in the availability of crucial nutrients which in turn, reduced crop yields and nutritional quality of the crops. Conventional fertilizer application methods frequently make inefficient use of nutrients and cause environmental pollution and waste. One of the pressing needs in agriculture today is to address these challenges by developing novel methods of providing nutrients to crops. Inefficient nutrient delivery has grim environmental implications. Too much fertilizer can be carried away by runoff to contaminate water supplies and generate algal blooms that deplete the oxygen, killing aquatic life. Also, nitrogen-based fertilizers have the potential to volatilize into the atmosphere as ammonia (NH3) or nitrous oxide (N2O), which acts as a powerful greenhouse gas and is 298 and 296 times, respectively, more powerful than CO2 in inducing global warming. A more efficient, sustainable and less harmful way to be able to provide around 9 billion people by 2050 with the food that they will need. One area where we need to do better and where significant inefficiencies and environmental problems are experienced is in nutrient delivery (due, in part to traditional fertilization methods). This section delves into the different maladies of misdelivery of nutrients and their repercussions, elaborately stating the existing research related to the concerned area.

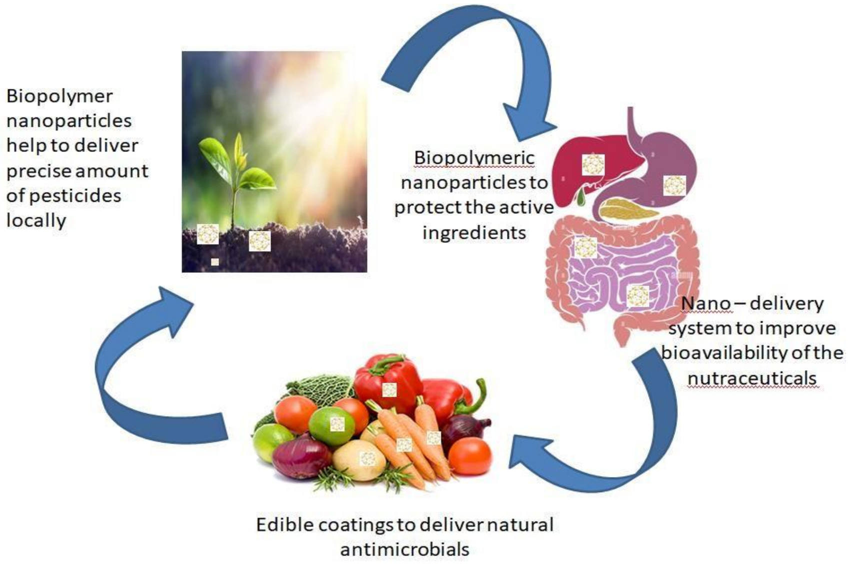

Figure 1: Developing nano-delivery systems for agriculture and food applications

Conventional fertilizers: Inefficiencies in conventional fertilizers have been a long-standing concern in agriculture (Dao *et al.,* 2020). These inefficiencies result in decreased plant growth and nitrogen uptake, hindering the overall productivity of crops. Addressing this issue requires a shift towards more efficient and sustainable methods of nutrient delivery, such as targeted placement techniques (Tilman *et al.,* 2002). Targeted placement techniques, such as bottom placement or localized application, have shown promising results in improving nutrient uptake and plant growth compared to conventional broadcasting methods (Smil *et al.*, 1999). Moreover, recent studies have demonstrated that bottom placement techniques can lead to a 23% increase in nitrogen uptake and up to a 48% improvement in crop growth, highlighting the potential benefits of implementing these techniques.

Nutrient losses: One of the major issues with conventional fertilizers is the high nutrient losses and environmental impact associated with their use (Townsend *et al.,* 2002, Cordell *et al.,* 2009, Foley *et al.*, 2005). One study found that the traditional broadcasting method resulted in a 1518% decrease in plant growth due to inefficient fertilization. This inefficiency is caused by the loss of a greater amount of fertilizer due to factors such as rain, irrigation, and sublimation by sun radiation. Existing studies suggest that between 30% and 50% of nitrogen, 10% to 25% of phosphorous, and 35% to 40% of potassium from conventional fertilisers are effectively used by crops (Diaz *et al.*, 2008, Conley et at., 2009, Smith *et al.*, 2004, Tubiello *et al.*, 2014). The rest of the nutrition will in the end be lost by means of leaching, runoff, volatilization and other ways in which form environmental pollution. For example, nitrogen leaching can introduce nitrates to contaminate groundwater, which in turn poses a health hazard to both humans and animals.

Macronutrient deficiencies: Plant nutrients are divided into primary macronutrients, which include nitrogen, phosphorus and potassium. Unfortunately, many soils lack adequate supplies of these nutrients, resulting in low crop yields (Rengel *et al.*, 2005, Zhang *et al.*, 2000, Fageria *et al.,* 2001). Plant growth is occasionally far from optimal with traditional fertilizers, simply because the deficiencies cannot be addressed in a powerful way. Targeted nutrient delivery systems (TaNDS) like nano-fertilizers promise to achieve a high upsurge in availability and uptake of macronutrients, helping to increase crop production and productivity as understudied by research (2020).

Micronutrient deficiencies: micronutrient deficiencies - especially elements like zinc (Zn) and iron (Fe) - are common (Alloway *et al.,* 2008). The burden of these deficiencies is twofold, they cause a reduction in crop yields as well as lead to human malnourishment due to a decrease in the micronutrient content of human diets, as plants grown in deficient soils have much lower levels of essential micronutrients.

Mechanisms of nanoparticle action in plants

The field of nanotechnology has seen a rapid growth in recent years, with nanoparticles (NPs) being increasingly utilized in various applications, including agriculture. Nanoparticles can interact with plants in complex ways, affecting their growth, development, and overall health.

Understanding the mechanisms by which nanoparticles influence plants is crucial for optimizing their use and minimizing any potential adverse effects.

One key mechanism by which nanoparticles can impact plants is through their antimicrobial properties (Fu, J. *et al.*, 2019). Metal nanoparticles such as silver, copper, zinc oxide, and titanium dioxide have been shown to possess potent antibacterial and antifungal activities, making them effective at controlling plant pathogens. Silver nanoparticles, in particular, have gained attention due to their ability to inhibit the growth of various fungal species that commonly infect crops. The precise mechanisms underlying the antimicrobial effects of nanoparticles are not fully understood, but they may involve disrupting cell membranes, interfering with cellular enzymes, and generating reactive oxygen species. By acting as antimicrobial agents, nanoparticles can potentially protect plants from disease-causing microorganisms, leading to improved crop yields and reduced reliance on synthetic fungicides.

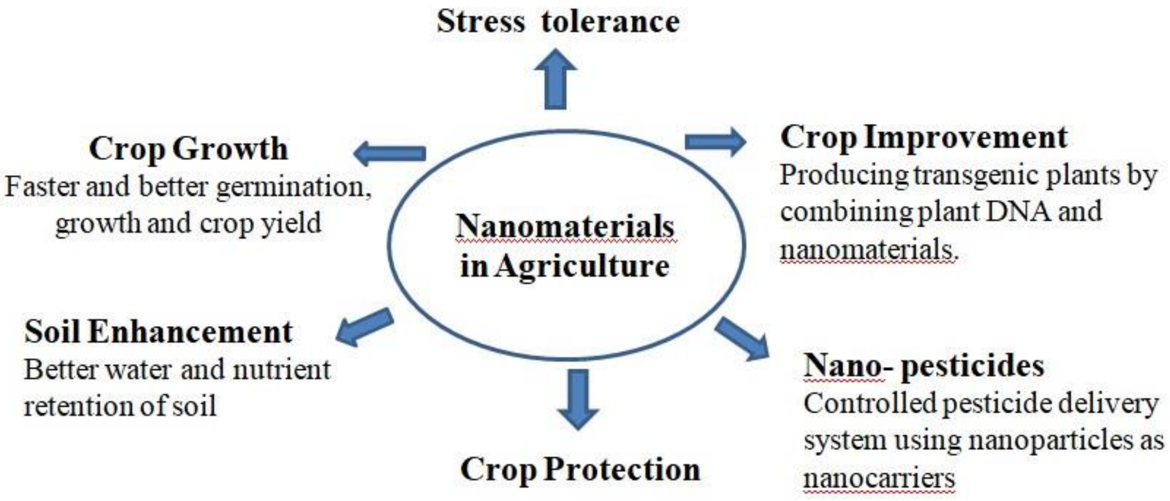

Figure 2: Opportunities and challenges for nanomaterials in agriculture

Uptake and Transport of Nanoparticles in Plants (Worrall EA *et al.*, 2019) (Rajani *et al.*, 2010) another mechanism by which nanoparticles can influence plant health is through their ability to be taken up and transported within plant tissues. Nanoparticles are known to be taken up by plants and transported through various tissues and organs, where they can modulate physiological processes. Nanoparticles can enter the plant system through the root system and translocate to other parts of the plant (Das, A *et al.*, 2024). The mechanisms of nanoparticle uptake and translocation in plants are not fully understood, but it is believed to involve complex processes such as diffusion, endocytosis, and ion channels. Nanoparticle size, shape, and surface properties can influence their uptake and transport within the plant.

Interaction with Plant Metabolism and Signaling: Nanoparticles can interact with and influence various metabolic and signaling pathways in plants. They have been shown to affect the activity of antioxidant enzymes, impact photosynthesis, and alter gene expression (Reid *et al.*, 2003). For example, nanoparticles can induce the production of reactive oxygen species, which can act as signaling molecules and trigger responses to environmental stresses (Reid *et al.*, 2003). Nanoparticles can also mimic the function of enzymes involved in oxidative metabolism, potentially enhancing the plant's ability to cope with heavy metal stresses.

Challenges and risks

Challenges and Risks Associated with Nanoparticle Use in Plants - While nanoparticles offer potential benefits, their use in plants also poses certain risks and challenges. Nanoparticles can induce phytotoxicity, leading to reduced plant growth, yield, and alterations in physiological processes. Nanotechnology in agriculture, particularly for enhanced nutrient delivery, presents several potential toxicity and safety concerns. These concerns primarily focus on the impact on soil health and human health. Nanomaterials, while beneficial for nutrient delivery, can pose risks to soil health. Their small size and high reactivity can lead to changes in soil chemistry and biology. Potential negative effects include:

- **a. Soil microbial balance**: Nanomaterials can alter the microbial community in the soil, potentially reducing beneficial microorganisms that play a crucial role in nutrient cycling and soil fertility.
- **b. Soil structure and pH**: The introduction of nanomaterials might impact soil structure and pH, affecting plant growth and soil aeration.
- **c. Bioaccumulation:** Certain nanoparticles might accumulate in the soil, leading to long-term ecological impacts that are not yet fully understood.

The impact of nanotechnology on human health is a significant concern, particularly through exposure to nanomaterials used in agriculture (Table 1). The potential risks include:

- **a. Ingestion and inhalation:** Humans may be exposed to nanomaterials through the consumption of food crops treated with nanoparticles or through inhalation during the application process. This exposure could lead to unforeseen health issues due to the unique properties of nanomaterials.
- **b. Toxicity:** Some nanomaterials may exhibit toxic properties at the cellular level, potentially leading to adverse health effects such as oxidative stress, inflammation, and even cellular damage.
- **c. Long-term health effects:** The long-term health effects of chronic exposure to nanomaterials remain largely unknown, necessitating comprehensive studies and monitoring.

Table 1: Nanotechnology for enhanced nutrient delivery in agriculture

Aspect	Description	Examples	Benefits	References
Nanoparticle Types	Various nanoparticles used for nutrient delivery, including nano-fertilizers, nano-pesticides, and nanocarriers.	Zinc oxide nanoparticles Titanium dioxide nanoparticles Chitosan nanoparticles	Enhanced nutrient uptake Controlled release Targeted delivery	Kah *et al.*, 2018
Nutrient Encapsulation	Process of encapsulating nutrients within nanoparticles to protect them and control their release.	Encapsulation of nitrogen, phosphorus, potassium in nanoclay Polymercoated nanoparticles for micronutrients.	Reduced nutrient loss Improved efficiency	Liu & Lal, 2015
Application Methods	Techniques used to apply nanoparticles to crops and soil.	Foliar spray Soil incorporation Seed treatment	Uniform distribution Minimized environmental impact	Fraceto *et al.*, 2016
Interaction with Soil and Plants	Interaction mechanisms between nanoparticles, soil components, and plant roots, including adsorption, absorption, and translocation	Adsorption of nanoparticles on root surfaces Translocation to plant tissues Interaction with soil microbes	Enhanced root growth Improved nutrient assimilation	Servin *et al.*, 2015
Environmental Impact	Evaluation of the environmental effects of using nanotechnology in agriculture, including toxicity and sustainability.	Biodegradable nanoparticles Reduction in chemical fertilizer use	Lower environmental toxicity Sustainable agricultural practices	Nair *et al.*, 2010
Benefits of Nanotechnology	Overall advantages of using nanotechnology for nutrient delivery in agriculture	Increased crop yields Enhanced stress tolerance Reduced application frequency	Higher productivity Cost effectiveness Ecofriendly solutions	Ghormade *et al.*, 2011

Conclusion:

Nanotechnology enables precise delivery of nutrients to plants, improving nutrient uptake efficiency and reducing wastage. The use of nanomaterials can lead to higher crop yields by ensuring that plants receive the necessary nutrients in optimal amounts. By minimizing the overuse of fertilizers, nanotechnology can reduce the environmental impact of agriculture, such as nutrient runoff and soil degradation. Potential toxicity to soil health and human health, along with regulatory and policy challenges, need careful consideration and management. Current regulations are evolving, and future policies must be adaptive to effectively address the risks associated with nanotechnology in agriculture. By enhancing the efficiency of nutrient use, nanotechnology helps in the conservation of resources, leading to more sustainable farming practices. The precise application of nanomaterials reduces the environmental footprint of agricultural activities by minimizing excess fertilizer use and associated pollution. Nanotechnology supports precision agriculture by enabling targeted delivery systems, which can improve crop management and reduce the need for chemical inputs. When used responsibly, nanotechnology can contribute to maintaining or improving soil health, which is vital for longterm agricultural productivity. Embrace the innovative potential of nanotechnology to drive advancements in agricultural practices, aiming for increased productivity and sustainability. Encourage collaboration among scientists, policymakers, farmers, and industry stakeholders to develop and implement safe and effective nanotechnological solutions. Advocate for the development of robust and adaptive regulatory frameworks that can evolve with scientific advancements and emerging evidence about the impacts of nanotechnology. Promote the integration of nanotechnology into sustainable agricultural practices, ensuring that the benefits are realized without compromising environmental and human health.

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SOIL HEALTH AND NANOPARTICLE DYNAMICS: UNVEILING THE MICROSCOPIC WORLD BENEATH OUR FEET

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Abstract:

To meet food demands of exponentially growing population use of chemical fertilizers, pesticides etc. is escalating. But the uncontrolled use of these chemicals leads to diminishing soil fertility status, food quality. About 50-70 % applied chemicals were lost due to mineralization, leaching, bioconversion affecting human health, microbial consortium and aquatic organisms. Because of these disadvantages, conventional practices need to be replaced by advanced technology like nanotechnology for sustainable agriculture. Nanotechnology works at nanoscale which has different mechanical, chemical and optical properties in comparison to bulk form. Nanotechnology aids in the development of nanoformulations which require minimum dose of fertilizers for slow release and nanobiosensors which detect the parameters of soil for assuring soil health which ultimately leads to improvement in food quality. Additional benefits of formulations based on nanomaterials include reduced toxicity due to the removal of organic solvents, increased efficacy due to increased surface area, solubility and improved mobility.

Keywords: Nanofertilizers, Nanotechnology, Soil Health, Agriculture, Heavy Metals, Zeolites

Introduction:

Agriculture plays a fundamental role in sustaining life on Earth by providing food to world. Factors like changing dietary habits and an expanding worldwide population are posing an increasing threat to global food security and its protection. Extreme weather events including droughts and floods, a lack of soil nutrients, and agricultural crop pests are major barriers to attaining global food security (Adisa *et al.*, 2019). Soil is considered as a fundamental lifesupporting mechanism which is an important part of terrestrial ecosystem (Singh *et al.*, 2012). In addition to being the primary substrate for plant growth and food production, soil health is essential for the regulation of biogeochemical cycles, water regulation, pollutant detoxification and nutrient cycle. It also helps in the management of biogenic gases, restoration of ecosystems and the preservation of biodiversity (Abhilash *et al.*, 2013). In order to evaluate soil health thoroughly, a variety of physical, chemical, and biological aspects must be considered. Physical and chemical factors comprised of soil texture, aggregation, moisture content, porosity, and bulk density and total carbon and nitrogen levels, organic matter content, mineral nutrients, cation exchange capacity (CEC) respectively. Biological factors like soil respiration, soil enzymes, biodiversity, microbial biomass carbon and nitrogen, and the existence of macro and mesofauna have the potential to affect physical and chemical factors (Fayiga and Saha, 2017).

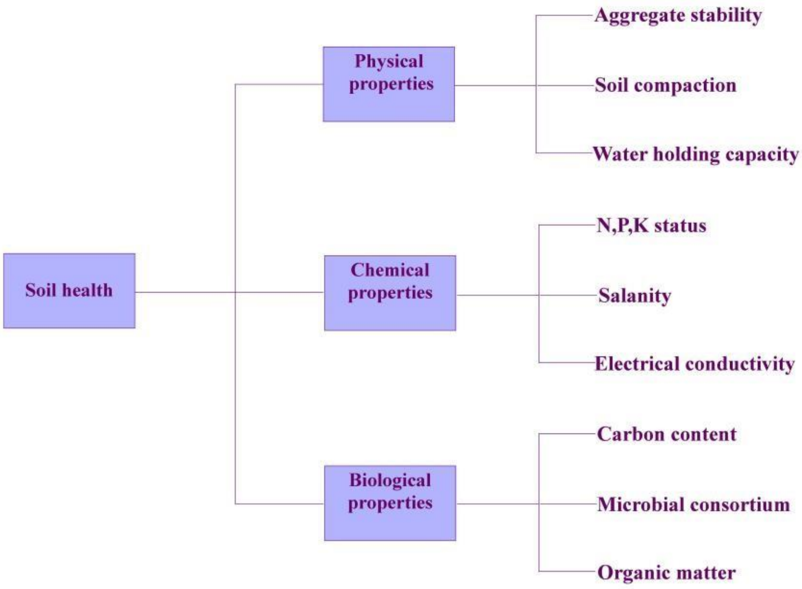

Figure 1: Parameters of soil health (Hasan *et al.*, 2020)

The ability of soil to support, maintain crop growth and productivity is decreasing worldwide as a result of intensive cropping, pollution, and other threats to the environment such heavy metal contamination, acidity, salt and natural calamities (Liu *et al.*, 2017). Agrochemicals like fertilizers are used for increasing food production but result in adverse effects on animals, beneficial soil bacteria and decrease soil fertility by altering soil mineral balance (Ragaei and Sabry, 2014). Fertilizer leaching involves the loss of water soluble nutrients that are necessary for plant development, which can lead to environmental problems including contaminated groundwater. The process of reaching phosphorus to water bodies happens by irrigation or precipitation leads to eutrophication (Thirugnanasambandan, 2021). Eutrophication severely reduces water clarity and lowers overall water quality. In addition, the increased photosynthesis brought on by eutrophication has the potential to drastically raise pH levels throughout the day and exhaust dissolved inorganic carbon (Chislock *et al.*, 2013).

Nanotechnology helps in precision farming which is sustainable in future. It involves increasing crop yield and minimizing environment pollution. It can be done by controlled release of fertilizers which require less dosage and nanosensors for monitoring soil health (Joshi *et al.*, 2019). Surface coatings of nanomaterials on fertilizers results in higher efficiency towards plants in comparison to conventional application because of their greater surface tension (Jatav and Nirmal, 2013). Effective nanoremediation techniques may be able to treat polluted soils locally rather than requiring expensive excavation and transportation (Rajendran *et al.*, 2022). Furthermore, nanotechnology can assist in the development of smart agricultural systems, which use sensors based on nanoparticles to monitor the condition of the soil, water and crop (Mittal *et al.*, 2020). For attaining maximum benefits of nanotechnology, biosensors and nanoformulations like nanofertilizers should be tested and commercialized at large scale.

Nanomaterials for soil health

Nanoformulations were used for site specific and controlled delivery of active compounds like fertilizers which maintain ecological balance by reducing surface runoff (Khot *et al.*, 2012).

Nanoformulations comprised of nanofertilizers, nanoporous zeolites, nanosensors.

Nanofertilizers

Nanofertilizers are the synthetic form of traditional fertilizers that aids in providing one or more types of nutrients during development of plant (Liu and Lal, 2015). These help in increasing food production, escalating resource efficiency and have less impact on ecosystem (Juárez-Maldonado *et al.*, 2019). Nanofertilizers can be transported by encapsulation of fertilizers within nanoparticles, which is accomplished in three different ways. The nutrients can be given as particles or emulsions at nanoscale dimensions, enclosed inside nanoporous materials, covered with a thin polymer film, or all three. (Rai *et al.*, 2012).

Table 1: Different types of nanofertilizers used on variety of plants (Chhipa, 2017)

Nanofertilizer	**Crop**	**Reference**
Au	Pearl millet (*Pennisetum glaucum*)	Parveen *et al.*, (2016)
Ca	Peanut (*Arachis hypogaea*)	Liu *et al.*, (2005)
CeO_2	Cucumber (*Cucumis sativus*)	Zhao *et al.*, (2014)
Carbon nanotubes	Date palm (*Phoenix dactylifera*)	Taha *et al.*, (2016)
	Tobacco (*Nicotiana tabacum*)	Khodakovskaya *et al.*, (2012)
Cu	Lettuce (*Lactuca sativa*)	Shah and Belozerova (2009)
CuO	Maize (*Zea mays)*	Adhikari *et al.*, (2016)
Mo	Chickpea (*Cicer arietinum*)	Taran *et al.*, (2014)
Fe/SiO_2	Barley (*Hordeum vulgare*), maize (*Zea mays*)	Najafi Disfani *et al.*, (2016)
ZnO	Mung bean (*Vigna radiata*), chickpea (*Cicer arietinum*)	Mahajan *et al., (*2011)
	Maize (*Zea Mays*)	Adhikari *et al.*, (2015)
	Clusterbean (*Cyamopsis tetragonoloba*)	Raliya and Tarafdar (2013)
FeO	Soybean (*Glycine max*)	Ghafariyan *et al.*, (2013)
	Pea (*Pisum sativum*)	Delfani *et al.*, (2014)
P	Soybean (*Glycine max*)	Liu and Lal (2014)

Nanofertilizers are categorized in 3 types: macronutrient nanofertilizers, micronutrient nano fertilizers, and nanoparticulate nano fertilizers.

1.1. Macronutrient nanofertilizers: This category includes nutrients that are needed in significant large quantities like phosphorus (P), potassium (K), magnesium (Mg), sulfur (S), nitrogen (N) and calcium (Ca) for proper growth of plants. When compared to traditional fertilizers, the amount and effectiveness of macronutrient nanofertilizer are increased when the volume to surface ratio of the nanomaterial is high. In this context, several researchers have created macronutrient nanofertilizer and applied it in field and laboratory (Chhipa, 2017).

1.2. Micronutrient nanofertilizers: Micronutrients are trace elements needed in minute amounts yet crucial for certain plant metabolic processes. Micronutrients in nanoform showed significantly improved plant growth and nutrition quality as well as increased bioavailability to the plants (Joshi *et al.,* 2019).

1.3. Nanoparticulate nanofertilizers: Nanoparticles exhibiting plant growth promoter activity included TiO_2, SiO_2, and carbon nanotubes (CNTs) (Joshi *et al.,* 2019).

Nanoporous zeolites

Nano clays and zeolites are used for improving fertilizer usage efficiency. They are included in class of naturally occurring minerals with a layered crystal structure resembling a honeycomb. Nitrogen, potassium, phosphorus, calcium, and an entire range of minor and trace nutrients may all be found within its network. Thus, it serves as a source of nutrients that are gradually delivered "on demand". Zeolites are mostly used in agriculture for the delayed release, storage, and collection of nitrogen. Zeolite, or aluminum silicates helps water enter and stay in the soil because of its high porosity and the capillary properties. It is a great way to improve non-wetting sands by acting as a natural wetting agent and facilitating the dispersion of water through soils (Prasad *et al.,* 2014).

Nanobiosensors

Compared to conventional methods, nanotechnology based sensors provide a number of benefits including high spatial resolution, low power consumption, real-time monitoring and the capacity to interact with wireless communication technologies (Parameswari *et al.,* 2024). The accurate and expeditious real time data obtained by estimating amount of nutrient, moisture content in soil helps farmer by increasing productivity, reducing cost and leaching of unused fertilizers. For example with the help of nanobiosensor made of gold nanoparticles, urea and urease activity can be evaluated (Deng *et al.,* 2016; Miguel-Rojas and Pérez-de-Luque, 2023). Some of the nanobiosensors are carbon nanotubes, graphene, quantum dots (QDs) and metal oxide nanoparticles (Parameswari *et al.,* 2024).

2.1. Carbon nanotubes: These are made up of rolled up graphene sheets. When nanotubes interact with the target change in electrical conductivity was recorded and used for analysis. They help in determining soil health factors like nutrients, presence of heavy metal or other contaminants (De Volder *et al.,* 2013).

2.2. **Graphene:** Consist of hexagonally lattice of carbon atoms arranged in single layer. They work on the electrical conductivity, resistance changes. These considered as a highly sensitive nanobiosensor for evaluating soil health (Suvarnaphaet and Pechprasarn, 2017).

2.3. Quantum dots: These are semiconductor made of nanocrystals having size range from 2–10 nanometers. When quantum dots interact with target it show changes in fluorescence or photoluminescence which was then analyzed (Geszke-Moritz *et al.,* 2013).

2.4. Metal oxide nanoparticles: Metal oxide nanoparticles, such as zinc oxide, tin oxide and titanium dioxide are extensively used for sensing application because of their special electrical, optical, and catalytic qualities. They show high surface to volume ratio, chemical stability, and adjustable bandgap which allow for the sensitive and targeted monitoring of soil health indicators including pH, moisture content, and gas emissions (Arafat *et al.,* 2012).

Nanomaterials for soil remediation

Anthropogenic activities including mining, industrial discharge, wastewater irrigation, heavy sewage sludge usage, and excessive fertilizer and pesticide use lead to soil contamination. These result in threat to food safety, ecosystem services and human health (Hasan *et al.,* 2020). Nanotechnology offers a efficient technique in which utilization of nanoparticles, such as nanoalginite, nZVI-bentonite, nano-carbon, nano-scale zero valent iron (nZVI), bentonite, and dendrimers, removes lead cadmium from polluted soil by working as efficient sorbents (Yavuz *et al.,* 2006).

Conclusion:

Nanotechnology is an emerging technology works in the matter ranging from 1 to 100 nm. The application of nanotechnology is projected to transform conventional agricultural practices into precision farming, offering significant hope for sustainable agriculture practices. Accurate farming is a balanced method for increasing agricultural growth, better fertilizer usage, less nutrient waste and less negative environmental effects. Nanomaterials which work at nanoscale were used in the form of nanoformulations, nanobiosensor and as a remediation tool to enhance soil properties which ultimately leads to increased yield and quality of food.

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HARNESSING NANOTECHNOLOGY FOR SUSTAINABLE CROP DEVELOPMENT

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Abstract:

A promising field has been identified by the name of nanotechnology that might possibly achieve sustainable crop production. There are two significant problems that modern agriculture face, the need to increase the productivity and, at the same time, the concern for the negative effects on the environment. The promising field of nanotechnology plays part through nano-sized preparations such as nano-fertilizers, -pesticides, -sensors and -emulsions to reinvent agriculture at large. Nano-fertilizers enhance soil nutrients that can be utilized in an efficient manner and decrease fretting loss and pollution. Nanoparticles-based pesticides display improved pest management and less hazard to health and ecosystem. The technology of nano-sensors plays a crucial role to support modern agricultural practices, where it is permissible to speak about precision agriculture that allows for the constant monitoring of the most important parameters and the efficient use of resources in agricultural production. Nano-emulsions are also promising techniques that allow improvements in solubility, stability, and increase the profiles of agricultural inputs. This chapter explores the nano technological improvement to the establishments of food production in a more sustainable and resilient manner addressing the major concerns for the modern agriculture as well as environment.

Introduction:

Agricultural production is not only fundamental to improving nutrition, but it is also the main source of income for many. Increased crop production is the key to economic and social development (Bogard *et al.*, 2018). A sustainable development meets not only the needs of the present generation it also encompasses the needs of future generations without compromising. In crop production, this involves adopting methods that minimize environmental harm while ensuring long-term productivity and profitability (Dönmez *et al.*, 2024).

Sustainable agricultural practices manage both natural resources and human resources, protecting the wellbeing of communities, strengthening local economies, promoting consumer health, and much more. Sustainable agriculture can help to mitigate catastrophic climate change, while also remaining resilient during extreme weather, drought, and flooding (Brodt *et al.*, 2011). Sustainable agriculture is an integrated system of plant and animal production practices having site-specific applications that will, over the long term: (a) satisfy human food and other needs; (b) enhance environment quality; (c) make efficient use of non-renewable resources and on-farm resources and integrate appropriate natural biological cycles and check points; (d) sustain the economic viability of farm operations; and (e) enhance the quality of life for farmers and society as a whole (Velten *et al.*, 2015). Sustainable crop development can be achieved by some of the common practices and pathways. For example, implementing regenerative practices and nature-based solutions, adopting agroforestry practices, reducing vulnerability and improving adaptive capacity against climate change impacts, advancing circularity in agriculture, adopting digital agriculture solutions for the farming supply chain, and ensuring predictability through innovative agri-technologies (Dönmez *et al.*, 2024).

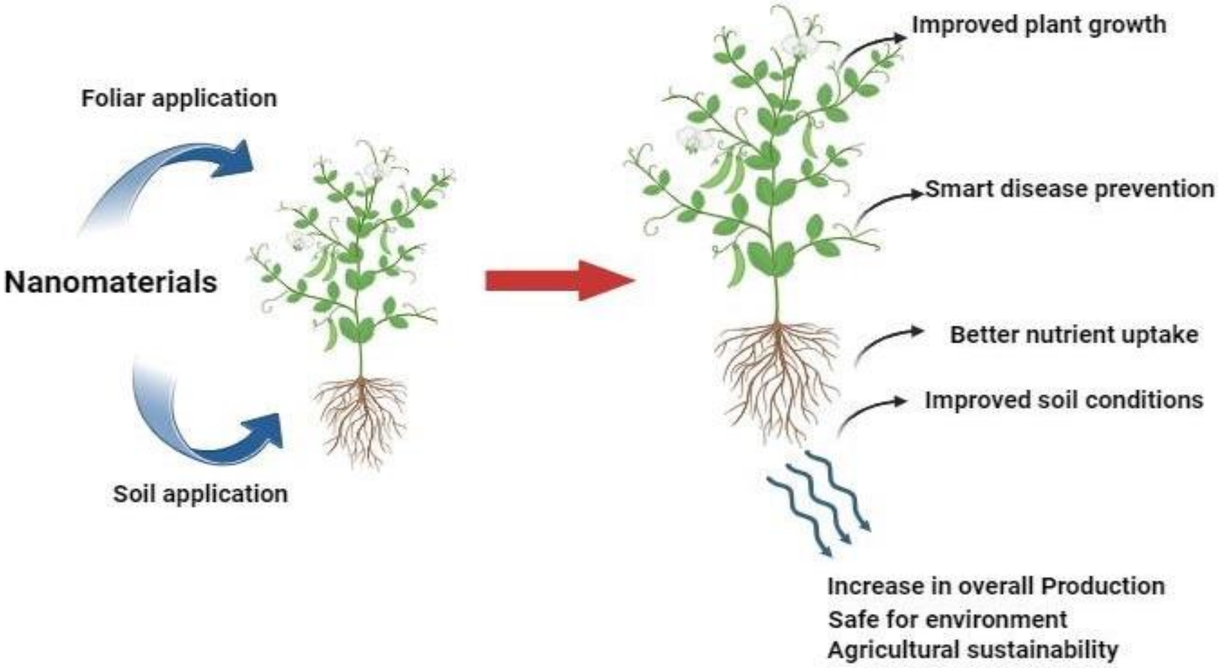

Figure 1: Role of nanomaterials in sustainable agriculture (https://app.biorender.com/illustrations/63258c28a7335e4580a0ed51?slideId=c9ec1e0f-47ed-4290890f-e4b9a49176a8)

Nanotechnology holds an enormous promise to address the challenges affecting agricultural production globally and solutions based on it are evolving fast (Prasad *et al.*, 2017). The term nanotechnology was invented at the University of Tokyo in 1971 by Professor Norio Taniguchi. Nanotechnology is the branch of technology that deals with dimensions and tolerances of less than 100 nanometer, especially the manipulation of individual atoms and molecules (Rajak, 2018). When we compare nanotechnology with traditional organic practices that include application of natural nutrient input such as compost and manure which take longer time as compared to nanotechnology-based fertilizers as a means of delivering nutrients to the plant. Nanotechnology leads to the controlled release of fertilizers; thus, the management of nutrients becomes efficient enough without using the excess amount. Organic methods also use the crop rotation and biocontrol, which is sometimes inadequate for controlling pests and diseases hence resulting in yield loss (Pudake *et al.*, 2024). Nanotechnology provides specialized nanopesticides and nanoinsecticides thus increasing crop protection and maximum yield. The agricultural practices of organic farming are environment friendly to some extent; however, they may still lead to nutrient runoff and water pollution. Nanotechnology-based fertilizers control such complications through their release mechanism, hence they have little effects on the environment (Wang *et al.,* 2022). Organic farming methods entail vast amounts of land and labor thus, cannot be adopted at large scales (Pudake *et al.,* 2024). On the other hand, nanotechnology applications such as nanofertilizers and nanopesticides are easier to produce and they can be applied in large scale farming. Overall, the future of the nanotechnology in crop development lies in approaches (Figure 2.) such as in nano-fertilizers, -pesticides, -sensors, -encapsulation, -emulsions etc. (Nongbet *et al.,* 2022). By adopting these nanotechnological advancements, we can move towards a more sustainable and resilient food production system (Figure 1.), ensuring the long-term viability of agricultural practices in the face of growing global demands and environmental concerns.

Nano-fertilizers

Nano-fertilizers are preparations of submicroscopic particle sizes in the range of 1 to 100 nm, release the nutrients in controlled manner and thus enable their slow diffusion into the soil (Nongbet *et al.,* 2022). The main challenge afflicting with the traditional fertilizers is their frequent application requirement in large quantities. This is due to their poor uptake efficiency because of fast conversion into forms that are unavailable for plant uptake. This has affected the soil and environment also, as the emission of dangerous greenhouse gases and increased eutrophication (Raliya *et al.,* 2017). On contrary to this, nano-fertilizers are designed in such a manner that they release nutrients gradually over a long period of time so as to minimize the nutrient losing and also addressing the ecological constraints in a much safer way (Ghormade *et al.,* 2011; Prasad *et al.,* 2017). During the preparation of nano-fertilizers, nutrients are attached to the nanomaterials acting as nanocarriers. Some of the nanomaterials are silica, Fe, ZnO, Al_2O_3, TiO_2, CeO_2, gold nanorods, quantum dots etc. Size of the nano-materials, content in the mixture, density, and chemical nature along with type of crop greatly influences the efficiency of nano-fertilizers (Singh *et al.,* 2021). Due to their large surface area/volume ratio, and higher mobility they increase access to plant nutrients and crop yield. Because of these characteristics, nano-fertilizers are deemed as a ‘system of nutrients’ (Jakhar *et al.,* 2022).

The development of nano-fertilizers remains a potential prospect of research in agriculture due to the controlled release of nutrients, high nutrient efficacy, low price, and low negativity to the environment (Prasad *et al.,* 2017). These are synthesized in varied manner and thus may of different types. For instance, they include; nanoscale fertilizers, additive fertilizers, coating fertilizers, and macronutrient fertilizers (Yadav *et al.,* 2023). These various kinds of nano-fertilizers indeed provide nutrients to the crops selectively helping to enhance yields and avoiding micro and macro environmental impacts (Basavegowda & Baek, 2021). Several scientific studies that were conducted on the use of nanofertilizers have established the fact that their use enhances the production and quality of crops, and also addresses environmental stress conditions. For instance, foliar spray of ZnO nanoparticles has been reported to increase grain/fruit yield and quality, stomatal conductance, and reduce drought stress in crops (Ding *et al.,* 2023). In the same manner, foliar application of Fe and Zn nanoparticles has been notable enhance the physiological quality of beans seed and yield under water stress condition. Other metallic nanoparticles like TiO_2 have been reported to enhance the growth and yield of crops under water deficit conditions (Ding *et al.*, 2023). Likewise, it has been revealed that foliar application of SiO_2 nano-particles enhanced the plant growth index under drought stress on the same crop (Ding *et al.*, 2023). Also, the investigation of low concentration of TiO_2 nanoparticles through leaves revealed that the nanoparticles displayed the capability to enhance the yield and quality of crops under drought stress (Singh & Chaudhary, 2020; Ding *et al.*, 2023). Research on the use of nano-fertilizers also shows that they enhance nutrient uptake in crops and thus, do not require the use of chemical fertilizers (Goswami *et al.*, 2024).

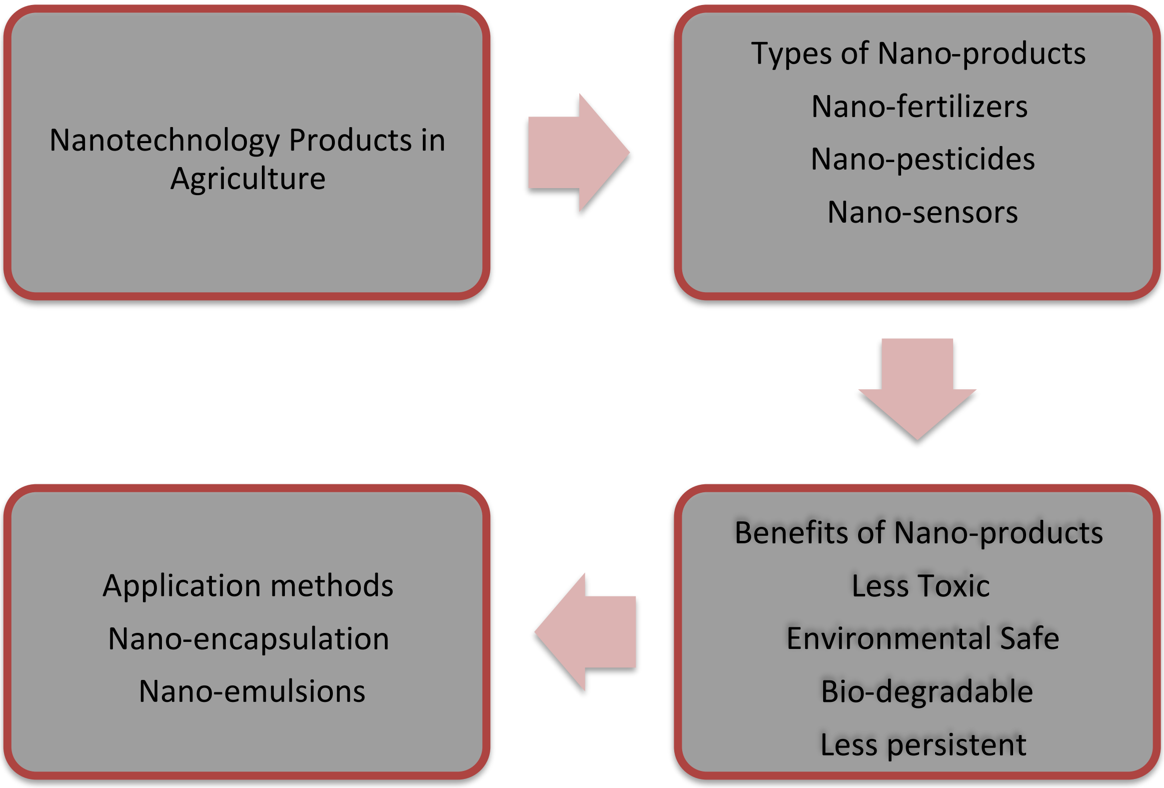

Figure 2: Nanotechnology products in agriculture

Over use of synthetic fertilizers has proven to be very expensive and also leads to environmental pollution including the soil, water, and even the air. It can be agreed that the recent development of nano-fertilizers has the potential for their sustainable use in modifying soil fertility, increasing crop yield and with minimal impacts on environment (Jakhar *et al.*, 2022). However, there are some drawbacks connected with them, such as using the different forms of nano-fertilizers, and the problem of delivering these forms to the target tissues in the soil. However, the utilization of nano-fertilizers is also associated with concerning human health and environmental risk. More importantly, a reality of the moment is the existence on the market of many products that largely cannot be termed "Nano" fertilizers much as they come in micron sizes, which limits the monitoring of nano-fertilizersin soil (Nongbet *et al.*, 2022). These particles have a number of toxic effects on plant systems. The incorporation of engineered nanoparticles (ENPs) in nano-fertilizers is a potential problem due to their transformation in the environment and nano-toxicity in both aquatic and terrestrial animal species. For instance, the graphene nanoplatelets and silver nanoparticles have been reported to possess genotoxic potential and hormonal imbalance in animals, thus, likely to affect human health (Bhardwaj *et al.,* 2022). In addition, they do not have standard guidelines for producing nano-fertilizers that question about their safety and risks for soil and water (Zulfiqar *et al.,* 2019; Bhardwaj *et al.,* 2022). They seem to pollute the soil and water resources given that nanoparticles can build up in soils.

On contrary, the researchers could not understand that how nanoparticles move in the environment, how they may accumulate in different organisms and tissues, and how long they can persist in the environment, which is critical information when assessing the long-term consequences of the use of Nano-fertilizers in ecosystems (Bhardwaj *et al.,* 2022). Consequently, despite the possible benefits of nano-fertilizers under the context of global sustainable agriculture, their safety and restricted application should be examined ceaselessly (Zulfiqar *et al.,* 2019).

Nano-pesticides

Nano-pesticides, the products of pesticides within corporate nanomaterial, are one of the possible ways of increasing agricultural yield with reduce the adverse effects of currently used pesticides (Prasad *et al.,* 2017). They are effective in pest management as they make a proactive contribution to the sustainable use of agrochemicals, thus leading to better pest suppression, reduced environmental harm, higher crop yield and less health risks from pesticide exposure (Chaud *et al.,* 2021). They target and penetrate more efficiently in pests, thus, providing improved pest management for most crops against the attacks by pathogens, insects, and weeds. Additionally, with the application of nano-pesticides it is possible to decrease the impact of the contaminated environment with pesticides due to the utilization of nanotechnology that enables to apply of smaller volumes of these chemicals and use of controlled-release formulations preventing pesticide leaching and runoff that affects water sources and ecosystems negatively (Chaud *et al.,* 2021).

The incorporation of nanomaterials in nano-pesticides also improve crop yields by increasing its resistance to pest attacks by increasing the long-lasting concentration of active ingredients provided by the nanocarrier (Bulbake *et al.,* 2017). Furthermore, nano-pesticides may also pose health benefits by reducing human susceptibility to pesticide exposure through the use of a smaller concentration of pesticides and decreasing unwanted impacts on organisms other than the target pests, thus protecting farmers, workers, and end consumers from toxic pesticide residues (Chaud *et al.,* 2021). Some of the crops that have been reported to get benefit from the nano-pesticides include rice, wheat, tomatoes, maize, and citrus crops, where nano-pesticides showed the ability to influence pests and diseases – such as the rice blast, wheat rust, aphids, and citrus. These examples revealed that nano-pesticides are valuable in making decision for the proper use of agrochemicals to foster sustainable agriculture as well as food security.

A peculiar class of nano-pesticides is liposome-based where liposomes, structures built from lipid bilayer, apply the pesticide to enhance their stability, bioavailability, and targeting abilities (Prasad *et al.,* 2017; Wang *et al.,* 2022). Besides that, they have lesser side effects and bioaccumulation in the environment as compared to normal formulations because of their application through precise delivery and controlled release properties (Li *et al.,* 2019). Other types are dendrimers, branched, macromolecular structures that are used as nanocarriers for pesticides as they provide controlled release and better targeting to enhance the efficacy of pesticides and reduce their unwanted impacts on the environment (Chauhan *et al.,* 2020). Nano-pesticides are not understood as an exhaustive science and therefore they require additional research to better determine if they are beneficial or detrimental to human health and the environment. Even the potential of using nano-pesticides to improve crop protection and production is not just limited to those examples, as more research and development are being conducted to establish new findings and improvements for those inventions. For instance, the new and improved controlled releasing formulation has been recently developed using nanoparticles namely Aba@HMS@CD@PDA, the results of which have been phenomenal in the eradication of pests including *Spodoptera litura* (Fabricius). Specifically, these nanoparticles, which combined abamectin with biodegradable polydopamine coating, β-cyclodextrin modified hollow mesoporous silica structure, displayed a more favorable release profile and better pesticidal efficacy than traditional formulations of abamectin (Li *et al.,* 2024). Furthermore, initiatives are being made to improve plant nano-bionics-based technologies which can be employed to overcome various problems, including nutritional deficiencies and pests, in agriculture that can make the process sustainable.

Carbon-based and metal-based nanoparticles including iron, copper, zinc, silver, and cerium are explored as they have the potential for better fertilizers and pesticides. Such potential benefits of these delicate substances include controlled release of nutrients, efficient uptake by plants, and effective control of pests which make these environment friendly products superior to the traditional materials (Bhaskar *et al.,* 2024). Another disadvantage is that the health hazards associated with nano-scaled pesticides are least explored. Due to properties such as instability, target specificity, and continual release, it is difficult to attribute each aspect of nano-pesticides completely to health hazards. Nanopesticides can be transported, bioaccumulated, and degraded more or less differently than chemicals that are in the conventional form (Nanda *et al.,* 2024). It is equally important to know more about the environmental sustainability of nano-pesticides where issues of persistence and accumulation in ecosystems are concerned. They stress the need to take the systems approach when it comes to the development of technology that is based on nano-bionics and is slated for future use in agriculture (Bhaskar *et al.*, 2024).

Nanoencapsulation

Nanoencapsulation is the process of entrapment of a bioactive compound in any state liquid, solid, or gaseous, in an inert matrix of nano-scale dimensions (Pateiro *et al.,* 2021). The substances that can be encapsulated are of different kind like nutrients, pesticides, herbicides, growth regulators, and other bioactive molecules usually required by plants. Nanoencapsulation of nutrients comes with a unique ability whereby nutrients are delivered directly to the plant cells in a way that increases their absorption and utilization (Karunaratne *et al.,* 2017). Slow-releasing nutrients are also delivered to the plant system initially in lesser quantity and then regulated in a steady manner over an extended period. This benefits the less frequent use of agrochemicals hence reducing their side effects on the environment and enhancing their effectiveness (Reddy *et al.,* 2024). Engineering of nanoparticles can allow them to reach discrete tissues or organs of plants to meet their nutritive requirements. Also, it assists in protecting the nutrients from degradation, leaching, or volatilization as well as from physical factors such as heat, moisture, or alteration in pH (Aamir Iqbal, 2020). In this way, the probability of polluting the soil, water, and air also reduced with consequent adverse effects on the living organisms, environment and ecosystems (Prasad *et al.,* 2017). Since nanoencapsulation controls the release of agrochemicals there is a decreased release of agrochemicals to the environment.

Nanoencapsulation increases the efficacy and availability of active substances because the particles are qualitatively and quantitatively more soluble and dispersible and are thus, absorbed better. This greatly enhances the bioavailability, which enables the transport of encapsulated compounds into the plants, thereby helping to enhance crop yield, quality, and production (Reddy *et al.,* 2024). Nanoencapsulation makes it possible to apply lower concentrations of agrochemicals but due to the technology used, the efficiency of the particular substance will remain high. This reduction in dosage does not only help in lowering the cost of the inputs that are used in the extraction process, but it is also effective in reducing wastage, making this method more sustainable (Prasad *et al.,* 2017). It can also be made stimuli sensitive whereby, they release the active ingredient on exposure to certain parameters such as pH, temperature, and moisture. This allows the delivery of encapsulated substances at the targeted site as well as the time of requirement thus enhancing the effectiveness and reducing side effects (Reddy *et al.,* 2024). In conclusion, nanoencapsulation enhances the efficiency and effectiveness of agrochemicals and also reduces their impact on environment. However, the large-scale production of nanocarriers containing nutrients can be somewhat complicated and expensive, which restrained their usage in agricultural practices (Amir Iqbal, 2020).

There is a need for legislation and risk management to be put in place in order to make safe and right use of products synthesized with nanoencapsulation (Amir Iqbal, 2020). Additionally, less information is available about their impact on soil properties, plant growth and overall ecosystem sustainability after a long application of nano-encapsulated nutrients in the soil. Thus, undoubtedly, they have appeared to have positive outcomes but need to be further studied to determine their effects and possible feasibility in the future (Balusamy *et al.,* 2023).

Nano-sensors

Nano-sensors are minimal real research instruments. These sensors have lower detection limits compared to their digital counterparts, and are portable as well as cheap (El-Chaghaby and Rashad, 2024). These are specialty instruments and are becoming popular since they have the ability to analyze and differentiate the chemical and physical properties or compounds at the molecular level in biological, agricultural and industrial settings that are otherwise hard to reach (Balusamy *et al.,* 2023; El-Chaghaby and Rashad, 2024). Closely related to real-time monitoring, these sensors are highly sensitive, and their design also allows for concurrent measurement of several parameters (Muthumalai *et al.,* 2023). Several forms of crop development are sustainable when it comes to nano-sensors that help in the real-time management of crops. Nutrient management is among the pivotal areas towards which nano-sensors can be chiefly employed. Instrumental to the goal of saving on costs and protecting the environment is the ability of nano-sensors to provide farmers with real-time soils nutrient status, which is useful in deciding on amounts of fertilizer to apply (Hossain *et al.*, 2020; Zain *et al.*, 2023; Hameed *et al.*, 2023).

Soil contains many nutrients in various structures, and they all emit different signals from a soil matrix. For example, nitrate concentrations in the soil and the level of ammonia in the soil indicate the occurrence of microbial abnormalities and soil-feeding insects (Zain *et al.*, 2023). It is possible for the farmers to assess nutrient concentration in the soil with better precision due to nano-sensors, so they can track essential elements such as nitrogen, phosphorus, and potassium. Nano-sensors indicate early symptoms of nutrient deficiencies in a plant and provide immediate action. In essence, utilization of nano-sensors allows farmers to analyze shifts of nutrient concentrations and plant reactions in realtime, so that condition causing nutrient deficiency or imbalance that affects crop output is detected early enough (Yi *et al.*, 2020). Several microbes and enzymes that are present in abundance in the soil are also effective in determining the soil acidity and quality of plant growth. Some of the microorganisms include the mycorrhizal fungi attach themselves to the roots of plants to help them to feed on the nutrients that they need for growth and development (Suman *et al.,* 2022). Some of the microorganisms also synthesize plant growth factors such as auxins and gibberellins hence promoting the growth and development of plant (Suman *et al.*, 2022).

Nano-sensors also play a crucial role to determine the level of moisture in soil that assists the farmers to regulate the quantity of water adequately thus availing water conservation (Hossain *et al.*, 2020; ElChaghaby & Rashad, 2023). However, one of the most significant uses of nano-sensors is in the prevention of pests and diseases. It helps to detect pests, pathogens, and diseases in the crops so that appropriate pest control activities such as, selective pesticide sprays or disease treatment processes can be initiated as and when required to prevent wastage of expensive insecticides (Rai *et al.*, 2012). The plants are sprayed with nano-sensors which are capable of identifying pests and diseases that affect the plants before the actual symptoms are manifested. Such early detection leads to timely application of the corrective measures that may help to control the disease spread and losses that farming experiences (Miguel-Rojas & Pérez-De-Luque, 2023). Some of the environmental factors include temperature, humidity, and soil moisture and mainly affect pest and disease development, and nano-sensors can help in its monitoring. These conditions are expressed as weather variables that are frequently checked by farmers so that they can make proper decisions in handling pests and diseases in their farms (Worrall *et al.,* 2018).

Miniature sensing devices can aid in revealing the kinds of pests and their density in the field. This helps in the utilization of efficient pest control methods that can avert extensive pesticide usage thus, reducing the risk of posing harm on beneficial organisms and the environment in general (MiguelRojas & Pérez-De-Luque, 2023). Nano-sensors can identify pathogens causing plant diseases due to their ability to detect viruses, bacteria, and fungi. When the diseases or pathogens have been correctly identified, farmers can commence the correct treatments like fungicides or biocontrol for diseases (Worrall *et al.,* 2018). They can enhance the use of pesticides by helping pest managers apply the right amounts at the right time and place, and by informing and guiding them of the abundance and locations of the pests that reduce the rate of chemical output that pollutes the environment (Yousef *et al.*, 2023). Even the use of nano-sensors can provide a platform to supplement other pest management systems like Integrated Pest Management (IPM). In this regard, nano-sensors enable the delivery of precise and timely information for improving the IPM working, which focuses on the least utilization of chemical pesticides and sustainable pest control. Additionally, nano-sensors perform a very important function in the field of soil management in agriculture as they are able to facilitate the measurement and monitoring of numerous parameters of soil as well that assist farmers in taking appropriate actions regarding irrigation, application of fertilizers, and control of pests (Miguel-Rojas & Pérez-De-Luque, 2023). For example, they can measure soil pH and this is very important in the determination of the type of soil, acidic or alkaline. It assists farmers in altering the acidity/alkaline content in the soil for better growth environment of various crops (El-Chaghaby & Rashad, 2023).

Nano-sensors can also measure the concentration of salts in the soil so that farmers can moderate the salt content. This is achieved through the selection of crops that can tolerate the specific level of sodium salts in the soil and water of the specific area, as salinity affects the growth and development of plants (El-Chaghaby & Rashad, 2023). They are capable of detecting various chemical compounds that are present in the soil like heavy metals or pesticides among others. This particular detection allows farmers to apply certain measures to prevent the contamination levels and ensure the quality of crops (El-Ghany *et al.*, 2023). It means that nano-sensors could help to determine and identify the overall condition and quality of soil depending on factors such as the amount of organic matter, microbial activity, and structure. This knowledge enables farmers to use appropriate strategies for neutralizing and enhancing the future quality of fertile soils (El-Ghany *et al.*, 2023).

A prime application of nano-sensors is in precision agriculture which is complemented by other technologies like GPS (global positioning system) and remote sensing. The use of data gathered on the parameters of the soil at micro-level will enable farmers to implement soil and site-specific decisions about the use of resources hence reducing depletion of the environment (El-Chaghaby & Rashad, 2023). In addition, they help in environment monitoring of parameters such as temperature, humidity and air quality to determine how it influence crop development and assist farmers in addressing environmental issues that may hinder productivity (Rai *et al.*, 2012). Besides these functions, nanosensors help to control the quality of crops by evaluation of sugar content, the level of ripeness, and nutritional value of the food product. This helps farmers to sell crops at the highest quality and hence minimizes losses that occur after harvesting of crops and, at the same time, offers better quality crops to the market (Rai *et al.*, 2012). In other words, nano-sensors provide solutions that are comprehensive in meeting the needs of sustainable crop development and equip farmers for making better decisions and improving their resource utilization while dealing with the problems that are harmful to the environment. Due to their flexibility, real-time monitoring capacity, and un-mechanized adaptability, nano-sensors are viewed as a sophisticated advancement of contemporary farming, which will possibly change the agricultural way of farming in order to encourage better farming as well as farming environment on earth (Rai *et al.,* 2012). There are however few shortcomings that include the high cost of production of nano-sensors and the ability to incorporate them in large fields may limit their accessibility by farmers, especially those in the developing world. However, the collaborations between research institution, industry and government agencies can assist in raising funds as well as support involving the use of affordable nano-sensors in data collection and analysis (El-Chaghaby& Rashad, 2023).

The specific nano-sensors are difficult to scale up for widespread application in the agricultural industry. Today, nano-sensors are still largely applied as prototypes and limited to the lab environments. Despite this disadvantage, there is need for further research and development so as to have better solutions as to improving the processes of manufacturing Nano-sensors and increase their capacity to handle large volumes of information or data.

Nano-emulsions

Nano-emulsions are kinetically stable liquid-in-liquid dispersions with droplet sizes of approximately 100 nm. Their small size results in desirable properties such as high surface area per unit volume, strong stability, an optically transparent appearance, and tunable rheology (Gupta *et al.,* 2016). One potential favorable effect derived from nano-emulsions concerns the improved capabilities for nutrient delivery. Nano-emulsions assist the delivery of nutrients inside plant cells with absolute precision to improve the growth rate of plants and decreases nutrient entry into the water table, and therefore, lower pollution levels. Further, nano-emulsions can enhance nutrient utilization as they reduce the particle size in the formulation thus improving the absorption rate of nutrients. This not only increases the yield of the products but also helps to minimize waste of fertilizers hence improving farm efficiency. The conventional fertilizers have negative impact on the environment by their polluting nature, soil toxicity and easiness of leaching through water-polluted sources, whereas nano-emulsions helps reduce these factors (Jakhar *et al.,* 2022). Moreover, they enhance plant growth and disease tolerance by enhancing the penetration into tissues and organs, providing nutrients and bioactive substances directly into cells, which increase defense mechanisms in plants. Moreover, many active ingredients such as pesticides, and herbicides, may also be transported through nano-sized colloids (Diez-Ortiz *et al.,* 2015). Previous findings have also established that nano-emulsions are efficient in different types of plants ranging from rice, wheat and vegetables (Mehmood *et al.,* 2024). This enhanced yield is attributed to better plant growth, nutrient absorption, and health through the new generation fertilizer in nano-emulsion.

Additionally, through nano-emulsions, water, and fertilizers, among other resources, can be conserved and optimally applied as they only reach the plant or the intended area. This reduces waste ages and resources used in improving agriculture farming and usage of resources in the farming process (Jakhar *et al.,* 2022).

In summary, the use of nano-emulsions provides multitude of advantages for effective boost of improved sustainable crops through increased nutrient delivery to plants, enhanced nutrient efficiency, reduced nutrient run-off and leaching, and improved crop health and yield. This incorporation into farming systems has the potential to make important impacts in cases of sustainability and productivity.

Conclusions:

In conclusion, it can be noted that the use of nanotechnology in agriculture can be a major revolution in changing the traditional practices in the development of new crops. It is with the nano-fertilizers, nano-sensors, nano-pesticides that are of much importance because they bring lots of positive aspects such as better nutrient management, control of pests, diseases, and water, and increased crop yields. This means that while nano-fertilizers provide the plant nutrients in a preserved and sustainable manner, they reduce the amount of unwanted nutrients released in the environment. Nano-sensors help farmers to conserve water and nutrients, detect pest invasions during early stages, and control the common diseases, thus improving the productivity of their crop. In general, the incorporation of nanotechnology in the pool of farming techniques will enhance its sustainability, minimize the deleterious effects of agricultural practices to the environment, and guarantee food security. Nevertheless, current limitations – mainly the concern for scalability, the relatively high costs, regulatory frameworks, and possible detrimental effects on the environment and human health resulting from nanomaterials require further research and development.

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PRECISION AGRICULTURE: A NANOTECH APPROACH TO OPTIMIZE RESOURCE UTILIZATION

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Abstract:

Precision agriculture has become a revolutionary method of sustainable farming aiming to increase productivity while reducing environmental effect. By improving resource utilisation in this context, integrating nanotechnology into numerous precision agricultural components, such as soil management, crop monitoring, and fertiliser delivery systems, offers viable paths to attain these aims. Nanosensors allow real-time data collection on soil conditions and crop health. Nanotechnology research is an interdisciplinary field. There have been recent attempts to boost agricultural output through intensive nanotechnology research. An increase in pest and disease resistance as well as a decrease in soil biodiversity were caused by the careless use of chemical fertilisers and pesticides brought about by the green revolution. Precision farming and material delivery to plants via nanoparticles or nanochips are the only biosensor technologies that can be made more advanced. The precise amount of nutrients and agrochemicals that plants need is delivered to them by means of conventional fertilisers, insecticides, and herbicides that have been nanoencapsulated. This process is done gradually and steadily. Kits for the early and rapid identification of plant virus diseases that use nanotechnology are likewise becoming more and more common. Nanotechnology's potential benefits and uses in precision farming are covered in this article.

Keywords: Nanotechnology, Precision Farming, Nanoparticle, Nanoherbicides, Nanopesticides.

Introduction:

Through the use of nanotechnology, precision agriculture is a cutting-edge method that aims to revolutionise farming operations by maximising resource efficiency and minimising environmental damage. Using cutting-edge technologies to track, control, and enhance crop production processes is the fundamental component of precision agriculture. The application of nanotechnology to precision farming has a number of game-changing advantages. For example, nanosensors can provide micro-level accuracy real-time data on the nutrients content, pest presence, and soil quality. Farmers may minimise waste and lessen environmental pollution by using this data to apply precise amounts of water, fertiliser, and pesticides where and when they are needed.

The culmination of all the efforts to increase farming's accuracy, maximise yields, and minimise waste is precision agriculture, or farming. It also reduces the amount of fertiliser and herbicides used. Essentially, it is crop management tailored to a particular site. Farmers utilise a variety of technology, including sensors, drones, robotics, software, automated vehicles, and the GPS (Global Positioning System). Environmental stresses and plant diseases can be tracked by field-sensing systems. Precision farming incorporates site-specific delivery and controlled release of nutrients, fertilisers, herbicides, and pesticides. Precision agriculture uses the "Internet of Nano Things" (IoNT), a combination of nanotechnology and the internet, to increase field output. Information that is available to farmers is coupled with temporal, spatial, and individual data from tested trials and the field. The salinity, pH, water, fertiliser, and other factors are all included in the comprehensive report that is produced. The farmers can more effectively monitor the field with the use of this report.

Precision agriculture is now a reality, and nanotechnology is being widely used in modern agriculture. Nanotechnology deals with particles less than 100 nm in size. Because of their small size, large surface area, and unique optical features, nanomaterials are employed in feeding, farming technique management, and plant protection. Different responses of plants to the nanoparticles are seen in terms of growth and metabolic processes. Because nanoencapsulation prevents dangerous materials from escaping or evaporating into the environment, it is essential for environmental protection. More potent, non-persistent insecticides, such as controlled-release formulations, need to be created to address this issue.

Modern agriculture has never seen anything like nanotechnology, which is poised to become a significant economic force. Its applications include:

(a) pesticides and fertilisers designed to improve crops.
(b) nanosensors and nanobiosensors for pathogen or hazardous residue detection.
(c) nanocarriers for enhanced genetic plant and beneficial microorganism manipulation.
(d) plant disease diagnostics.
(e) animal health and productivity.
(f) postharvest handling.

Applications of nanotechnology in precision farming for plant growth and germination

A fundamental input that determines production is seed. The percentage of germination in seeds is traditionally used to assess their quality. Seeds exhibit a lower germination percentage in fields, even if laboratory germination rates are greater (80–90%). A number of academics have recently looked into how nanomaterials affect plant germination and growth in an effort to promote their use in agriculture. In several crop species, including onion, spinach, tomato, and potato, nanomaterials like ZnO, TiO_2 , FeO, Zn, Fe, Cu-oxide, and hydroxyfullereness have been shown to improve crop growth and development while also improving crop quality. The process of germination and seedling growth is aided by nanoparticle’s capacity to penetrate the seed coat and increase water absorption and utilisation. Seyed Saeid Hojjat and Hamidreza Hojjat. (2015) reported that among the concentrations (0, 10, 20, 30 and 40μg mL^{-1}), application of 10μg mL^{-1} of Nano silver proved best by giving the highest values for percent seed germination, germination mean time, seedling vigor index and seed germination index. To improve tomato seed germination, Khodakovskaya *et al.,* (2009) from the University of

Arkansas, USA, employed carbon nanotubes. Zinc-oxide nanoparticles used in the plant agar method were found to enhance the growth of mung bean and chickpea (Cicer arietinum) seedlings at low concentrations. When concentrations were above acceptable levels, nevertheless, a decrease in the rates of growth of roots and shoots was noted (Mahajan *et al.*, 2011).

Nanotechnology in soil management

Nano fertilizers have been established as sustainable approaches for precision farming as a result of the steady use of nanotechnology in agriculture over the previous decade. Although the enormous amounts of fertilisers applied have significantly increased output, they also negatively impact the beneficial soil bacteria. Because of runoff and pollution, most fertilisers are unavailable to plants. This issue can be resolved with fertilisers coated in nanoparticles. Because of their higher surface tension than typical surfaces, nanoparticles hold materials from plants more firmly than traditional surfaces, which makes them potentially useful in slowing the release of fertilisers. Larger particles are additionally shielded from the surface by nanocoatings. Since the bulk of Indian soil is lacking in these macronutrients, particularly nitrogen, nanocoated urea and phosphate and their sustained release will be helpful in meeting soil and crop demands. Deliveries of enormous quantities of fertilisers have significantly increased production, but they also damage the beneficial soil microorganisms. Due to runoff and pollution, the majority of fertilisers are unavailable to plants. This issue can be resolved with fertilisers covered in nanoparticles. Due to the increased surface tension of nanoparticles than ordinary surfaces, they are able to hold materials from plants more firmly than traditional surfaces, which makes nano materials potentially useful in slow release fertiliser applications. Furthermore, bigger particles are shielded from the surface by nanocoatings. The bulk of Indian soil is lacking in these macronutrients, particularly nitrogen, therefore nanocoated urea and phosphate and their sustained release will be helpful to meet soil and crop demands.

With the help of nanofertilizers, fertiliser losses can be avoided, as well as unintended nutrient interactions with microbes, water, and air. This is achieved by balancing the release of nitrogen and phosphorus during plant absorption. Multiple artificial and natural nanoparticles have been developed, along with the ability to nanoencapsulate nutrients in mineral, polysaccharide, or liposome nanocapsules, in order to modify conventional dosages to more balanced doses. Nutrients in bulk or nanosize form, which may be extracted from different parts of plants to increase yield, output, and growth, are known as nano fertilisers.

Like ordinary fertilizers nano fertilizers can be applied directly to soil or foliage. The particles' small size permits them to enter the pores of roots and plants, and their reactivity and solubility are also advantageous. Some Nano fertilizers products have already been commercialized.

1 Nano-GroTM (plant growth regulator and immunity enhancer)

2. nano-Ag AnswerR (microorganisms, mineral electrolyte, and sea kelp)

3. TAG NANO (NPK, PhoS, Zn, Ca, and others)

4. protein lactogluconate;
5. Probiotics, vitamins, seaweed extracts, humic acid, and other micronutrients.

The aim of developing new nanomaterials based on metallic, polymeric, and inorganic nanoparticles is to enhance intelligent nano systems that can take up and immobilise nutrients, releasing them into the soil gradually to increase fertiliser efficiency. Moreover, pest and disease detection in crops is made possible by the development of nanosensors. Metallic nanoparticles of various kinds, such as Ag, Fe, Cu, and Zn, can be applied as insecticides or fungicides to fight dangerous bacteria and fungus, or as nanofertilizers to enhance plant growth and seed germination.

Crop protection and management with nanotechnology, the use of nanopesticide

Although there are several uses for nanotechnology in crop protection, its most popular application is in the development of slow-release encapsulating agrochemicals. Utilising various types of nanoparticles, including silver nanoparticles, aluminium oxide, zinc oxide, and titanium dioxide, to combat Sitophilus oryzae-caused rice weevil and Bombyxmori-caused grasseries disease in silkworms, as well as the baculovirus BmNPV (B. mori nuclear polyhedrosis virus), were studied. Nano-encapsulation of pesticide allows proper absorption of the chemical into the plants due to slow and sustained release and has a long lasting and persistent effect unlike the normal agrochemicals. The environmental effects of synthetic pesticides are negative, but they are quite particular to the pests they are meant to kill. To increase the potential applications of nanoparticle-based pest management technologies, it is necessary to move towards botanical insecticides using nanotechnology.

Fungal diseases among crops cause major loss to the production. Though many fungicides are commercially accessible, applying them to plants has negative consequences as well. In order to solve this issue, nanotechnology has a significant potential impact. Researchers have been testing nanoparticles as antifungal treatments to combat harmful fungi. Tests have been conducted on the antifungal activity of zinc oxide (35–45 nm), silver (20–80 nm), and titanium dioxide (85–100 nm) nanoparticles against Macrophomina phaseolina, a significant soil-borne pathogen of oilseed and pulse crops. At lower concentrations than zinc oxide and titanium dioxide nanoparticles, a greater antifungal impact was seen with silver nanoparticles. When maize was treated with nanosilica (20–40 nm), it was tested for resistance to Aspergillus niger and Fusarium oxysporum, two phytopathogens, in comparison to bulk silica. Aspergillus niger and Fusarium oxysporum phytopathogens have been tested for resistance in maize treated with nanosilica (20–40 nm) against bulk silica. In leaf extracts obtained, the plant treated with nanosilica exhibited a greater expression of phenolic compounds (2056 and 743 mg/mL, respectively) and a lower expression of stress-responsive enzymes against these fungi.

In terms of disease index and expression of total phenols, phenylalanine ammonia lyase, peroxidase, and polyphenol oxidase, at 10 and 15 kg/ha, these data demonstrated significantly greater resistance in maize treated with nanosilica compared to bulk. In order to combat phytopathogens, silica nanoparticles can be employed as a powerful substitute antifungal agent.

Using nanotechnology for weed control and using nanoherbicide

Weeds pose the biggest threat to agriculture since they take up nutrients that crop plants would otherwise be able to use, therefore decreasing agricultural productivity. The environmentally friendly elimination of weeds from crops is facilitated by the use of nanoherbicides. Herbicides can also be included in polymeric nanoparticles to ensure environmental safety. In order to stop resistant weed species from growing, nanoherbicides mix in with the soil's particles. Rhizomes and tubers, two viable underground plant elements that serve as a source of new weeds, are killed by it. They prevent food stores in the root system from being glycolyzed by targeting a particular receptor in the roots of the target weeds.

Precision farming has long aimed to optimise crop yield while reducing the amount of fertilisers, pesticides, herbicides, and other inputs by tracking environmental factors and taking focused action. Utilising computers, sensors, global satellite positioning systems, and remote sensing equipment, precision farming measures extremely localised environmental conditions and aids in pinpointing the type and location of issues as well as if crops are growing as efficiently as possible. In the end, precision farming using smart sensors would enable increased agricultural productivity by giving farmers precise information, which will enable them to make more informed decisions.

Table 1: Nanoparticles used as herbicides in commercial vegetable crops (Dulhan *et al.*, 2017)

Sr. No.	Nanoparticles	Nanoherbicides used against herbs/weeds	References
1.	Silver nanoparticles chitosan Encapsulated paraquate	*Eichhornia crassipes*	Namasiviyam *et al.,* 2014
2.	Cu	*Cucurbita pepo*	Musante *et al.,* 2012, Hawthorne *et al.,* 2012
3.	CuO	*Raphanus sativus, Lolium perenne and Lolium rigidum*	Atha *et al.,* 2012
4.	CuO and ZnO	*Fagopyrum esculentum*	Lee *et al.,* 2013
5.	Cu	*Elodea densa*	Nekrasova *et al.,* 2012
6.	CuO and ZnO	*Cucumis sativus*	Kim *et al.,* 2012

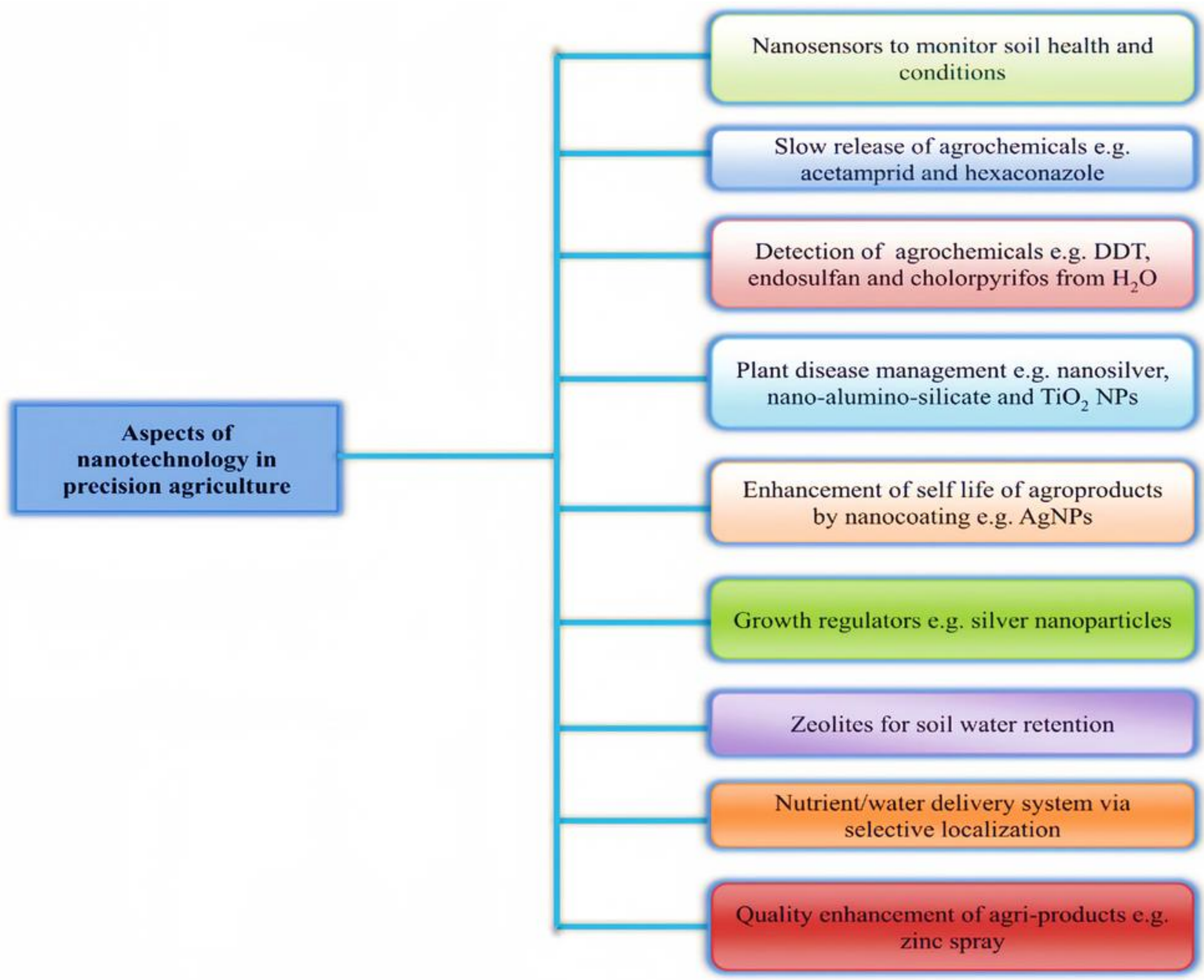

Figure 1: Aspects of nanotechnology in precision agriculture (Dulhan *et al.*, 2017)

Using nanotechnology to manage water

Increased crop productivity and more efficient use of water can result from using nanotechnology to improve agricultural water management. By removing pollutants and impurities from irrigation water, nanofilters can make the water fit for farming. Because of the tiny holes in these membranes, particles can be removed selectively according to their size and charge. Silver, iron oxide, and titanium dioxide nanoparticles can be utilised to cleanse water for use in agriculture. Water quality factors including pH, temperature, dissolved oxygen, and nutrient levels can be tracked with nanosensors. Farmers can minimise waste and maximise water use with the aid of this real-time monitoring. By increasing the soil's ability to store water, hydrogel-like nanoparticles can lessen the requirement for regular irrigation. Water can be absorbed and released by these particles, enhancing plant development and productivity.

Using nanotechnologies to control postharvest diseases

Globally, decomposition accounts for a large portion of food loss both before and after harvest. Bacterial and fungal degradation accounts for most of these losses.Many products derived from nanotechnology, like nanofilms and nanosensors, can be applied to postharvest management to extend the postharvest life of fruits and vegetables. Chitosan nanoparticles, for instance, have been employed to modify the mycelial growth of numerous fungal species, thereby enhancing the quality of chilli seeds. Silver nanoparticles, or nano silver (2.5 nm), have been used in the development of antimicrobials. Mango anthracnose is caused by C. gloeosporioides. The growth of this pathogen was inhibited by combining traditional fruit-coating material with a 1 percent concentration of nanosilver. This combination significantly reduced the disease when compared to the control. A number of research have recently been published on the synthesis of nanolaminate coatings and their potential synthesis into functional nanoparticulated nanomaterials for use as active or additive carriers.

Work on nanotechnology done in India

- IFFCO one of the biggest fertiliser manufacturing cooperatives globally, has produced nanotechnology-based products such as nano-nitrogen, nano-zinc, and nano-copper to enhance agricultural production.
- IIT Madras has utilised nanotechnology to remove arsenic from water.
- Using iron and sulfur-rich nanoparticles, a group of scientists at IIT Kanpur have increased agricultural productivity.
- To increase the phytochemical content of several mung bean types, Iqbal *et al.*, create a procedure for elicitor-based nanotechnology-assisted in vitro shoot multiplication and callus induction.

Challenges and prospects for the future

Precision agriculture can benefit greatly from the use of nanotechnology in a variety of ways, including satellite farming, nanopesticides, nanofertilizers, nanosensors, and nanoparticle allowed target delivery. Understanding the long-term effects and environmental implications of employing nanotechnology is the main task that lies ahead. To generate fully proofed, standardised, affordable, and environmentally acceptable nanomaterials, interdisciplinary research across several fields of expertise is needed. It is possible to meet each plant's unique requirements through research and experimentation, as different plants, farms, and agricultural landscapes require distinct environments. Though technology has drawbacks of its own, precision agriculture is a wonderful invention that allows farmers to monitor crops, remotely access their farms, and identify water stress, fertiliser availability, soil fertility, pest infestations, and other issues. We can gain more understanding if we conduct research and use nanomaterials in the field together. Additionally, a brief understanding would help with the large-scale development and application of nanomaterials and nanobased techniques.

Thus, in the not too distant future, agri-tech nanotechnology may be used as a cutting-edge tool to help address the problem of world hunger. Many scientists think that smart nanotools from nanotechnology would enable higher productivity on high-tech farms with less resources used. By thwarting plant diseases and averting crop failure, it promotes the creation of innovative, potent agrochemicals for plants, such as nanopesticides and nanofertilizers which support sustainably sustainably smart agriculture.

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NANOTECHNOLOGY IN PRECISION AGRICULTURE: ENHANCING EFFICIENCY AND SUSTAINABILITY

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Abstract:

Precision agriculture, an innovative farming management concept, leverages cutting-edge technology to meticulously observe, measure, and respond to inter- and intra-field variability in crops, revolutionizing modern farming practices. Integrating nanotechnology into this advanced paradigm promises to elevate agricultural efficiency and sustainability to unprecedented levels. Nanotechnology introduces an array of novel tools, including nanoscale materials and devices designed for the precise delivery of nutrients and pesticides, which significantly reduce waste and environmental contamination. These nanomaterials facilitate targeted delivery systems that ensure optimal use of inputs, thereby minimizing adverse environmental impacts. Moreover, nanosensors offer real-time, continuous monitoring of soil and plant health, providing farmers with detailed, actionable data on crop conditions. This enables more informed decision-making and optimized resource use, ensuring timely and precise interventions. Nanosensors enhance the ability to manage variables such as nutrient levels, moisture content, and the presence of pathogens or pests, fostering a proactive approach to crop management. In addition, nanotechnology contributes to superior water management practices, which are crucial for sustainable agriculture. Nanosensors can accurately monitor soil moisture levels, supporting efficient irrigation and water conservation. Advanced nanomaterials enhance water filtration and purification, ensuring that crops receive clean and adequate water supplies. This book chapter delves into the transformative potential of nanotechnology in addressing the myriad challenges faced by modern agriculture. It emphasizes nanotechnology's pivotal role in promoting sustainable farming practices, boosting crop yields, and reducing agriculture's ecological footprint. By harnessing the unique properties of nanomaterials, precision agriculture can achieve unparalleled levels of productivity and environmental stewardship. This exploration underscores nanotechnology's promise in driving a more resilient, efficient, and sustainable agricultural future.

Introduction:

Precision agriculture has emerged as a transformative approach to modern farming, leveraging advanced technologies to optimize crop production and resource management. This method focuses on the detailed observation, measurement, and response to variability in crops within fields, enabling farmers to enhance productivity and sustainability (Zhang *et al.,* 2021). However, as the global population continues to grow and climate change imposes new challenges on agricultural systems, there is a pressing need for even more innovative solutions (Zain *et al.,* 2023). Nanotechnology, the manipulation of matter on an atomic or molecular scale, offers significant potential to revolutionize precision agriculture. By integrating nanotechnology into farming practices, it is possible to achieve unprecedented levels of efficiency and sustainability (Goyal *et al.,* 2023). Nanomaterials can be engineered to deliver nutrients and pesticides with pinpoint accuracy, reducing waste and minimizing the environmental impact of these chemicals. Additionally, nanosensors can provide real-time, high-resolution data on soil and plant health, facilitating more precise and timely interventions (Duhan *et al.,* 2017). This introduction explores the intersection of nanotechnology and precision agriculture, highlighting the ways in which nanoscale innovations can address current agricultural challenges. From enhancing crop yields to conserving water resources and reducing chemical inputs, nanotechnology holds promise for a more sustainable and productive agricultural future (Yadav *et al.,* 2023). As we delve into the applications and benefits of this technology, it becomes evident that nanotechnology is not just an enhancement to precision agriculture, but a pivotal component in advancing the efficiency and sustainability of farming practices globally (Nazir *et al.,* 2020).

Fundamentals of nanotechnology in agriculture:

Nanotechnology in agriculture revolves around the utilization of materials and devices at the nanometer scale, typically ranging from 1 to 100 nanometers, to enhance various aspects of farming practices (Raliya *et al.,* 2017). At this scale, materials exhibit unique physical, chemical, and biological properties that can be exploited to develop innovative agricultural solutions. The fundamental applications of nanotechnology in agriculture include the development of nanofertilizers and nanopesticides, which allow for the precise delivery of nutrients and pest control agents directly to the target sites, thus minimizing environmental contamination and improving efficiency (Raliya *et al.,* 2017). Additionally, nanosensors play a crucial role in precision agriculture by providing continuous monitoring of soil health, moisture levels, and crop growth, enabling farmers to make data-driven decisions (Pandey and agriculture, 2020). These sensors can detect and transmit information about various parameters in real time, allowing for timely interventions and optimized resource usage. Furthermore, nanotechnology can enhance the efficiency of water use through advanced water filtration and purification systems, ensuring that crops receive clean and adequate water supply (Acharya and Pal, 2020). Overall, the integration of nanotechnology into agricultural practices offers a pathway to more sustainable, efficient, and resilient farming systems, addressing the pressing challenges of modern agriculture while supporting global food security (Sahoo *et al.,* 2023).

Applications of nanotechnology in precision agriculture:

- **Nanosensors:** Nanosensors embedded in soil or plant tissues enable real-time monitoring of key parameters such as soil moisture, nutrient levels, and pest infestations. These nanosensors provide valuable data for precise irrigation, fertilization, and pest management decisions, leading to optimized resource use and improved crop yields (Chanu and Singh, 2022).
- **Nanofertilizers:** Nanofertilizers offer targeted delivery mechanisms for essential nutrients, enabling efficient nutrient uptake by plants. Nanoencapsulation techniques enhance nutrient stability, release kinetics, and uptake efficiency, resulting in improved nutrient use efficiency and reduced environmental impact (Shaikh *et al.*, 2021).
- **Nanopesticides:** Nanoformulations of pesticides exhibit enhanced efficacy, reduced environmental toxicity, and prolonged release characteristics compared to conventional formulations. Nanopesticides enable targeted delivery to pest-infested areas, minimizing off-target effects and reducing chemical usage in agriculture (Mc Carthy *et al.,* 2018).
- **Nanomaterials for soil remediation:** Nanomaterials such as nanoclays, nanoscale zero-valent iron (nZVI), and carbon nanotubes hold promise for soil remediation applications. These nanomaterials facilitate the removal of contaminants, such as heavy metals and organic pollutants, from soil and water, thereby improving soil health and environmental sustainability (Lindgren *et al.,* 2018).

Table 1: Applications and benefits of nanotechnology in precision agriculture

Application Area	Nanotechnology Tool/Approach	Benefits	References
Soil Health Monitoring	Nanosensors	Precise measurement of pH, nutrients, and moisture levels	Raliya *et al.,* (2018); Jha *et al.,* (2019)
Crop Health and Disease Detection	Nano-biosensors	Early detection of diseases and stress, reduced pesticide use	Prasad *et al.,* (2017); Parisi*et al.,* (2015); Kim *et al.,* (2018)
Environmental Monitoring	Nano-biosensors	Continuous monitoring of temperature, humidity, light	Chen *et al.,* (2018)
Precision Irrigation	Nano-encapsulated water	Efficient water use, prevention of overirrigation	Khot *et al.,* (2012);
Nutrient Delivery	Nanofertilizers	Targeted nutrient delivery, reduced waste and runoff	Sekhon (2014) Kumar *et al.,* (2018); Gogos *et al.,* (2012)
Pest and Disease Control	Nanopesticides	Targeted pest control, reduced environmental impact	Ghormade *et al.,* (2011); Schrand *et al.,* (2010)
Data Analytics	Nanosensors integrated	Real-time data	Liu and
and Decision Making	with AI and IoT	analytics, predictive modeling	Lal (2015); DeRosa *et al.,* (2010)

Challenges and considerations:

While the integration of nanotechnology into precision agriculture holds great promise, several challenges and considerations must be addressed to fully realize its potential. These challenges span technical, economic, environmental, and social dimensions, each posing significant hurdles to the widespread adoption and successful implementation of nanotechnologies in agriculture (Adeyeye and Science, 2017).

Technical challenges

- **Manufacturing and scalability:** The production of nanosensors and other nanodevices at a scale large enough for widespread agricultural use remains a major technical challenge. Ensuring consistency, reliability, and quality in mass production is critical (Garnett, 2013).
- **Durability and stability:** Agricultural environments can be harsh, with varying temperatures, humidity, and exposure to chemicals. Ensuring that nanosensors and nanodevices remain functional and accurate under these conditions is essential for their long-term use (Haddad *et al.,* 2016).
- **Integration with existing systems:** Compatibility with existing agricultural machinery and data management systems is necessary for seamless integration. Developing standardized interfaces and protocols is a key technical hurdle (Hwalla *et al.,* 2016).

Economic challenges

- **Cost:** The initial development and deployment costs of nanotechnology can be high. Small-scale and resource-limited farmers might find it difficult to invest in these advanced technologies without financial support or incentives (Fan and Brzeska, 2016).
- **Economic viability:** Demonstrating the cost-effectiveness of nanotechnology applications in agriculture is crucial. Farmers need to see a clear return on investment through improved yields, reduced inputs, or other economic benefits (Watson *et al.,* 2018).

Environmental challenges

- **Nanomaterial toxicity:** The potential toxicity of nanomaterials to soil health, beneficial microorganisms, and non-target organisms poses environmental risks. Understanding and mitigating these risks is essential to avoid unintended ecological consequences (McClements *et al.,* 2021).
- **Persistence and degradation**: The environmental persistence and degradation pathways of nanomaterials need thorough investigation. Ensuring that nanomaterials do not accumulate in the environment or enter the food chain is a significant concern (Tansey and Worsley, 2014).

Social and regulatory challenges

- **Public perception and acceptance**: Public skepticism and concerns about the safety and ethical implications of nanotechnology in food production need to be addressed through transparent communication and education (Yadav *et al.,* 2023).

- **Regulatory frameworks**: The regulatory landscape for nanotechnology in agriculture is still evolving. Clear guidelines and standards are required to ensure the safe and responsible use of nanomaterials in farming practices (Zain *et al.*, 2023).
- **Ethical considerations**: Ethical issues related to the deployment of advanced technologies in agriculture, such as the impact on small farmers and traditional farming practices, must be carefully considered (Ofori and El-Gayar, 2021).

Data management and privacy

- **Data security**: The use of nanosensors generates vast amounts of data. Ensuring the security and privacy of this data is critical to protect farmers' proprietary information and maintain trust (Pandey and Innovation, 2018).
- **Data integration**: Efficiently integrating data from nanosensors with other sources and systems for comprehensive analysis requires robust data management infrastructure (Bhattacharya *et al.,* 2023).

Table 2: Some technological aspect of nanotechnology

Aspect	Description	References
Improved Delivery of Agrochemicals	Nanoformulations enable precise targeting and controlled release of pesticides and fertilizers, reducing waste and environmental impact.	Chanu *et al.*, 2019
Sensor Technology	Nanosensors provide realtime data on soil conditions, moisture levels, and nutrient content, optimizing resource management	Chaing *et al.*, 2021
Enhanced Crop Monitoring	Nanoscale imaging technologies allow for early detection of diseases, pests, and nutrient deficiencies, enabling timely interventions.	Fan *et al.*, 2018
Smart Delivery Systems	Nanoencapsulation delivers nutrients and growth regulators directly to plants, enhancing uptake efficiency and minimizing losses.	Duhan *et al.*, 2017
Environmental Impact	Nanomaterials reduce the volume of chemicals needed, minimizing runoff and soil contamination, thus promoting sustainable farming practices.	Gor *et al.*, 2019
Precision Water Management	Nanotechnology enables efficient water use through targeted irrigation and soil moisture monitoring, conserving water resources	Hadddad *et al.*, 2016
Biodegradability and Safety	Developing biodegradable nanomaterials ensures minimal environmental persistence and reduces long-term ecological risks.	Goyal *et al.*, 2014
Challenges	Issues such as cost, regulatory concerns, and potential health risks require careful consideration and ongoing research.	Ofori*et al.*, 2021

Future perspectives:

The future of nanotechnology in precision agriculture holds immense potential, promising to further revolutionize farming practices and address the challenges of global food security and environmental sustainability. As research and development in this field advance, several key areas are likely to see significant growth and innovation (Prasad *et al.,* 2017).

Advanced nanosensors and smart systems

- **Next-generation nanosensors**: Future nanosensors will likely become even more sophisticated, with enhanced sensitivity and specificity for detecting a broader range of environmental and biological parameters. These advanced sensors will provide farmers with more detailed and accurate data, facilitating better decision-making (Mishra *et al.,* 2017).
- **Integrated smart systems**: The integration of nanosensors with smart systems, including Internet of Things (IoT) networks and artificial intelligence (AI), will enable more autonomous and precise farming. These systems can analyze real-time data, predict trends, and implement corrective actions automatically, optimizing resource use and crop management (Mishra *et al.,* 2019).

Sustainable nanomaterials

- **Eco-friendly nanomaterials**: Research is increasingly focused on developing biodegradable and environmentally friendly nanomaterials. These materials will minimize ecological impact and reduce concerns about nanomaterial accumulation and toxicity in the environment (Usman *et al.,* 2020).
- **Targeted delivery systems**: Future developments in nanomaterials will enhance the precision of nutrient and pesticide delivery systems. These systems will release their contents only under specific conditions or in response to certain triggers, ensuring that inputs are used efficiently and effectively (Pramanik *et al.,* 2020).

Enhanced crop protection and nutrition

- **Nano-encapsulated agrochemicals**: Nano-encapsulation techniques will improve the stability and efficacy of agrochemicals, such as fertilizers and pesticides. Encapsulation can protect these chemicals from degradation and control their release, reducing the required quantities and minimizing environmental impact (Pramanik *et al.,* 2020).
- **Nanobiosensors for early detection**: Nanobiosensors capable of detecting plant pathogens and stress signals at an early stage will become more prevalent. Early detection will enable timely interventions, preventing significant crop losses and reducing the need for broad-spectrum pesticides (Gor *et al.*).

Precision breeding and genetic engineering

- **Nanotechnology in breeding**: Nanotechnology will play a crucial role in precision breeding, allowing for more accurate manipulation of plant genomes. Techniques such as targeted gene editing using nanoparticles can accelerate the development of crops with desirable traits, such as drought resistance and enhanced nutritional content (Manjunatha *et al.,* 2016).

- **Gene delivery systems**: Nanoparticles can serve as carriers for delivering genetic material into plant cells, facilitating the development of genetically modified crops with improved performance and sustainability (Chugh *et al.,* 2021).

Environmental monitoring and climate resilience

- **Comprehensive environmental monitoring**: Future nanosensor networks will provide comprehensive monitoring of environmental conditions, including soil health, water quality, and atmospheric parameters. This data will help farmers adapt to changing climate conditions and manage resources more sustainably (Shukla *et al.,* 2024).
- **Climate-resilient farming practices**: Nanotechnology will contribute to the development of climate-resilient farming practices by enabling precise control over agricultural inputs and environmental conditions. This will help mitigate the impacts of climate change on crop production (Raliya *et al.,* 2017).

Policy and education

- **Supportive policy frameworks**: Future perspectives include the development of supportive policy frameworks that encourage the adoption of nanotechnology in agriculture. Policies will focus on ensuring safety, promoting research, and providing financial incentives for farmers to adopt these technologies (Lyons *et al.,* 2018).
- **Education and training**: Increasing awareness and understanding of nanotechnology among farmers and agricultural professionals will be essential. Educational programs and training initiatives will equip farmers with the knowledge and skills needed to effectively use nanotechnologies in their operations (He *et al.,* 2019).

Conclusion:

Nanotechnology presents transformative opportunities for precision agriculture, offering solutions that enhance efficiency, sustainability, and productivity. By enabling precise delivery of nutrients and pesticides, real-time monitoring of soil and plant health, and improved water management, nanotechnology addresses some of the most pressing challenges in modern agriculture. Nanosensors, with their ability to provide detailed, realtime data, empower farmers to make informed decisions and optimize resource use, reducing environmental impact and increasing crop yields. However, the successful integration of nanotechnology into agricultural practices requires addressing several challenges. Technical hurdles, such as manufacturing scalability and sensor durability, need to be overcome. Economic considerations, including the high initial costs and demonstrating economic viability, are crucial for widespread adoption. Additionally, environmental and regulatory concerns regarding the toxicity and persistence of nanomaterials must be thoroughly investigated and managed. Despite these challenges, the future of nanotechnology in precision agriculture is promising. Ongoing research and innovation are expected to produce advanced, eco-friendly nanomaterials and more sophisticated nanosensors, further enhancing the capabilities of precision agriculture. Supportive policy frameworks, educational initiatives, and interdisciplinary collaboration will be essential in facilitating the adoption of these technologies. In conclusion, nanotechnology holds significant potential to revolutionize precision agriculture, driving advancements that contribute to global food security and environmental sustainability. By addressing current challenges and leveraging future innovations, nanotechnology can play a pivotal role in creating a more efficient, sustainable, and resilient agricultural sector.

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NANOMATERIALS IN PEST MANAGEMENT: BALANCING EFFICACY AND ENVIRONMENTAL IMPACT

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Abstract:

Agriculture is a primary sector for food production but pest become a major concern to food security. Application of pesticides was considered as a best conventional method to manage pest but indiscriminate usage leads to toxicity and environmental concern. But at the present time nanotechnology is considered as a best alternative for managing pest. Nanotechnology uses active formulations at nano levels. Major applications of nanomaterials are controlled and targeted delivery and with use of nanosensors early detection of pests are possible. The nanomaterials have high surface area to volume ratio, exceptional physical properties and biological reactivity. Nanomaterials helps in enhancing the active compound stability, reduction in dosage requirements and increasing pesticide performance. The desired material was transferred in the form of nanocapsules, nanosuspensions, nanogels, nanoemulsions etc. Therefore, use of nanomaterials for managing pest is considered as best method due to its property to increase efficacy, specificity and sustainability for future.

Keywords: Nanomaterials, Nanobiosensors, Microorganism, Pest Management, Target, Nanopesticide

Introduction:

Presently, prime concern around the globe is to ensure food security to exponentially growing population. By 2050, it is expected that there will be 9 billion people on the planet and increase in the need of food from 59 to 98% (Duro *et al.*, 2020; Bhatnagar *et al.*, 2024). Food production is impeded by biotic and abiotic stresses. Pest is the most concerning biotic factor and leads to about 20- 40 % yield loss globally each year (FAO 2019). To overcome this situation, chemical pesticides such as herbicides, insecticides, fungicides are used extensively because of their effectiveness, economical and easy to use property (Khan *et al.*, 2023). But these traditional methods are inadequate for pest management and even cause health risk to human, livestock, decline in soil fertility, resistance in pests, toxicity, pollution (Yousef *et al.*, 2023). About 0.1 % of pesticide used affects the target organism and remaining 99.9 % dispersed in the ecosystem causing pollution and toxicity (Dutta and Baruah, 2020). Due to less awareness, improper use of protective measures everyday around 700 people die due to pesticide poisoning and thousands of lives were affected (Khanal *et al.*, 2023). Short time exposure of pesticide to human causes diarrhea, vomiting, rashes, burning of skin whereas long time exposure cause birth defects, diminished intelligence, reproductive deformities and cancer (Alavanja *et al.*, 2004; Thundiyil *et al.*, 2008; Sharma *et al.*, 2020).

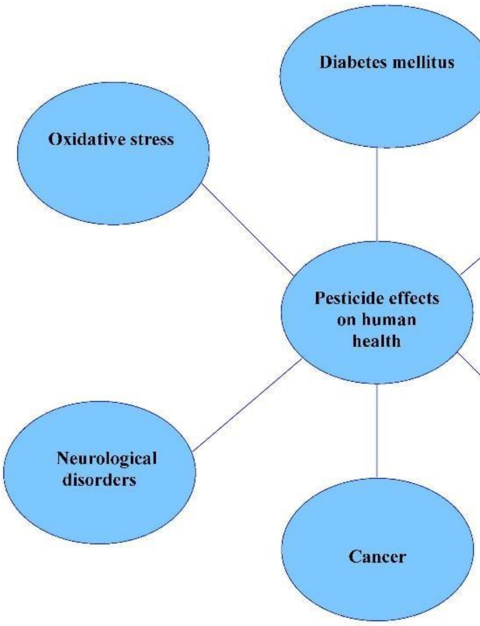

Figure 1: Effects of chemical pesticides on human health (Jatoi *et al.*, 2021)

Now a days, nanotechnology is considered as a best alternative over conventional practices for pest management to reduce dependency on chemical pesticides. Nanotechnology has a potential to form matter with atomic level specificity (Vinutha *et al.*, 2013; Saw *et al.*, 2023). Nanotechnology helps in enhancing the stability of active ingredients, reducing dosage requirements, conserving agronomic inputs, and raising pesticide performance (Jasrotia *et al.*, 2018; Rikta and Rajiv, 2021). Nanomaterials have found applications in bioengineering, optical engineering, agriculture, medical, industry, military, security, and nanoelectronics (Ahmed *et al.*, 2015). Nanomaterials shows diverse shapes comprising nanoparticles, nanopowders, nanoclusters, nanosheets, nanotubes and nanofibres having one or more dimensions between 2 nanometers to 100 nanometers (Tamta *et al.*, 2024). Nanoparticles are nanocarriers for targeted delivery of insecticides, herbicides, fungicides and RNA interference materials (Worrall *et al.*, 2018) The utilization of nanoparticles is increasing day by day due to their high surface area to volume ratio, exceptional physical properties and biological reactivity (Wahab *et al.*, 2024). Nanoparticles are used for pesticide delivery and nanosensors. In order to improve targeted delivery and diminish environmental impact, nanoparticles have been shown to be more effective at encapsulating and delivering pesticides to pests. Like conventional practices, nanoparticle pesticides help insoluble active ingredients become more soluble or allow for gradual release in order to avoid premature breakdown (Adisa *et al.*, 2019; Guleria *et al.*, 2023). Nanopesticides and formulations (emulsion, encapsulation, crosslinking) requires carrier materials like silica, chitosan, wheat gluten etc. to increase water solubility, escalating dispersion and dissolution abilities (Prasad *et al.*, 2017). Nanobiosensors are used to supervise crop status, soil health and pest. Nanobiosensors aids on site detection of pest by monitoring released pheromone or wing vibrations (Kansotia *et al.,* 2024). To get maximum benefits of nanotechnology, different nanobased techniques must be produced and commercialized after conducting risk assessments and trials of the product.

Nanopesticide

Nanopesticides are considered as a good alternative of traditional practices used for pest control. Conventional methods have low utilization rate, bulk usage, decreased bioactivity, lesser solubility, diminished durability. On the other hand nanopesticides are more efficient, interact precisely with target pest even at lower doses because of its large surface area. In addition, nanopesticides not only improve the solubility of pesticides but also efficiently transport necessary components to the intended species, increasing their bioavailability (Shekhar *et al.,* 2021). The combination of plants, microorganisms, and their derivatives with nanopesticides is a major step toward environmentally responsible and long-lasting pest management techniques. Even with their enormous potential, they are yet elusive to be widely adopted (Aithal and Aithal, 2015).

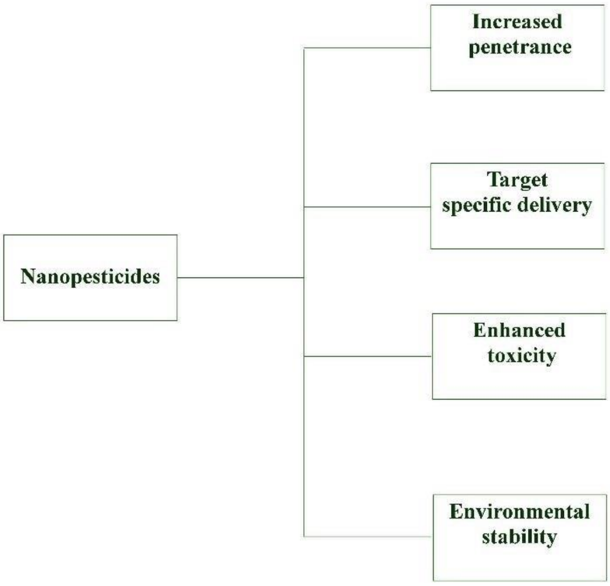

Figure 2: Advantages of nanopesticides (Saw *et al.*, 2023)

Different types of nanopesticide formulations

Nano formulations have several uses including improving the solubility of insoluble active components, gradual release of active compound, guarding against degradation and making it easier to identify the activity of enzymes in systems (Thakur *et al.,* 2018). When materials or substances are reduced to nanoparticle size, two possible results can be observed i.e. an improvement in the characteristics of the particles or a decrease in the functions of the materials. Major alterations occur in nanoactive materials: they become more reactive to electromagnetic forces, have a higher surface area-to-volume ratio, exhibit random Brownian motion, and are subject to quantum mechanical processes (Rani and Sushil, 2018). Nanopesticide formulations consists organic (polymers) or inorganic (metal oxides). Some foremost nanoformulations are listed as nanoemulsions, nanosuspensions, nanocapsules, nanogels, nanospheres (Table 1).

1. Nanoemulsions – The active ingredient is dispersed as nanosized droplets within an oil-in-water (O/W) emulsion, sometimes referred to as a nano-emulsion. When a pesticide shows partial solubility in water, it spontaneously forms a stable emulsion when mixed with surfactants and water and referred as thermodynamically stable nano-emulsions. Because the active component is insoluble at first, a two-phase system arises between the pesticide and surfactant. However, if the mixture is constantly agitated, the pesticide droplets become more evenly distributed over time and attain kinetic stability (Tamjidi *et al.,* 2013). For example, neem oil was used to create an oilin-water nano-emulsion for insect control using Tween 20 as a surfactant.
2. Nanosuspensions - Pesticides are dispersed as solid nanosized particles in aqueous solutions to generate nano-suspension. Surfactant molecules are confined at the particle surface in these formulations; their non-polar portions interact with the solid pesticide, while their polar segments extend into the aqueous environment. Using this method, for instance, scientists have created aqueous dispersions of β-cypermethrin, novaluron, and nanopermethrin (Rajna *et al.,* 2019).
3. Nanocapsules – Nanocapsules are made up of polymer like membrane within which active compound is present at nanoscale. This covering helps in slow release, protection from environment and specific target delivery of active compound (Ezhilarasi *et al.,* 2013).
4. Nanogels – Aqueous dispersions of hydrogel particles with physical and chemical crosslinks at nanoscale form nanogels. In comparison to natural pheromones, these nanogels are more stable and have better mechanical, chemical, and heat resistance. Highly volatile pheromones such methyl eugenol (ME) block evaporation and protect from environmental variables including light, water and air exposure that might degrade them (Zannat *et al.,* 2021).
5. Nanospheres – The bioactive component of these structures is uniformly distributed throughout a polymer matrix, giving them their characteristic uniform vesicular appearance. For instance, it has been feasible to produce bifenthrin-containing nanospheres stabilized by polymers (Rajna *et al.,* 2019).

Solid nanoparticles as nano-pesticides

Some of metal and metal oxides act as potential pesticide such as silver nanoparticles, cadmium nanoparticles, aluminium oxide nanoparticles. They act as a carrier to deliver active compound. Silver nanoparticle (Ag) is used against *Colletotrichum gloeosporioides*, *Fusarium culmorum*, *Phythium ultimum*, *Trichoderma* sp., *Scalerotinia sclerotiorum* and *Rhizoctonia solani* (Joshi *et al.,* 2019).

Table 1: Different types of nanoparticles as active compound delivery system (Sumithra and Ranjitha, 2023; Yousef *et al.*, 2023)

Nanoparticle	Active compound	Pest	Reference
Nanocapsules	Essential oil *of Carum copticum*	Diamond back moth (*Plutella xylostella*)	Jamal *et al.*, 2013
	Thifluzamide and validamycin	*Rhizoctonia solani*	Cui *et al.*, 2020
Nanogels	LC@NFBs	Foliar application	Cao *et al.*, 2021
	Methyl eugenol	Oriental fruit fly (*Bactrocera dorsalis)*	Bhagat *et al.*, 2013
Nanoemulsions	Vitex Negundo essential oil	*Avena fatua* and *Echinochloa*	Mustafa and Hussein, 2020
	Norcanthridin	*Plutella xylostella*	Zeng *et al.*, 2019
	Aniba essential oils	*Aspergillus flavus, Aspergillus niger* and *Fusarium solani*	Zeng *et al.*, 2019
	Alpha-cypermethrin deltamethrin, lambda cyhalothrin, and permethrin	*Culex pipiens* larvae	Taktak *et al.*, 2021

Nanobiosensors

Nanobiosensors are the devices that integrates a biologically generated sensitive element with physiochemical transducer. Nanobiosensor is comprised of three parts i.e. **1.** Biological sensitized probe which consist of biological entity like nucleic acids, proteins, lectins, microorganism or biomimic of desired sample. **2.** Transducer which act as a middle man between probe and detector. It works by detecting physical changes and then transform changes to an electrical output. **3.** Detector which receives signals from transducer and pass it to microprocessor where it is amplified and analyzed (Mushtaq and Faizan, 2020). Farmers can use nanobiosensors to detect nutrient deficiency, soil fertility, crop status, and invasion of certain pests or diseases. Extensive crop damage can be prevented by observing real time data of biosensors and potential issues addressed (Wahab *et al.*, 2024). Nanobiosensors helps in detection of pheromones and wing vibrations of insect pest even at low levels. Some types of nanobiosensors help in pest population monitoring, early detection of pest which further aid in precise targeting with minimal quantity of pesticide (Kansotia *et al.*, 2024).

Conclusion:

Nanotechnology has the potential to transform modern agriculture with its inventive innovations. Nanotechnology has the potential to tackle major difficulties related to sustainable growth in the agricultural sector mainly in the area of managing pest. To deliver the desired active compound use of nanomaterials is considered as a best tool which facilitates dose reduction, long term protection, increased efficiency and reactivity. In comparison to conventional emulsifiable concentrates applied in fields, nanopesticide delivery method have low amount of organic solvent. This change can augment penetration capabilities, increase wettability, and improve droplet dispersal. The selectively releasing ability of nanoencapsulated pesticides reduces pesticide losses in the environment. At lower concentrations, their increased surface area allows for efficient control of specific pests. With its long-lasting effectiveness, high efficacy, and good safety profile, nanotechnology offers a sustainable pest control strategy with significant crop protection potential.

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NANO-WONDERS: HARNESSING NANOTECHNOLOGY FOR SUSTAINABLE AQUACULTURE GROWTH

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Abstract:

Aquaculture is increasingly recognized as a vital component of global food security, providing a significant portion of the world's seafood. However, its sustainability is threatened by various challenges, including environmental degradation, disease outbreaks, and resource limitations. Nanotechnology offers a promising avenue to address these challenges by providing innovative solutions for enhancing aquaculture practices. This chapter explores the potential applications of nanotechnology in sustainable aquaculture growth. It discusses how nanomaterials can be utilized in various aspects of aquaculture, including water quality management, disease prevention, and feed supplementation. Nanoparticles such as silver, copper, and titanium dioxide have demonstrated antimicrobial properties, offering effective means to control pathogens in aquaculture systems while minimizing environmental impact.

Introduction:

As the global population burgeons and economies expand rapidly, ensuring an adequate supply of high-quality food, particularly protein, poses a significant challenge (Samanta *et al.*, 2022). The escalating demand for nutritious sustenance has turned attention towards aquatic protein resources, fostering a remarkable growth in global aquaculture (Shah and Mraz, 2020). Aquatic sources offer easily digestible protein, essential healthy fats, and a spectrum of vital micronutrients, serving billions worldwide. Moreover, aquaculture not only offers a potential platform for rural employment and livelihood but also holds substantial export earning potential, bolstering national GDP through income generation (Sarka *et al.*, 2022).

According to the Food and Agriculture Organization (FAO, 2016), fish contribute approximately 17% of animal protein and 7% of total protein consumed by humans, with per capita fish consumption witnessing a steady rise from 9.0 kg in 1961 to 20.5 kg in 2017 (FAO, 2018; Fajardo *et al.*, 2022). Presently, global fish production stands at approximately 177.8 million tons in 2019, with an estimated economic value nearing US$ 380 billion (FAO, 2020). Projections suggest that global fish production may reach around 181 million tons by 2030, with aquaculture poised to contribute over 60% of this output (Park *et al.*, 2018). However, the aquaculture sector faces challenges necessitating technological innovation, including disease control, efficient drug use, water quality improvement, and tailored fish production (Fajardo *et al*. 2022; Nasr-Eldahan *et al.*, 2021).

These challenges are exacerbated by environmental concerns such as eutrophication and the looming threat of global climate change, which manifests in high temperatures, elevated methane and CO2 levels, and altered hydrological patterns (FAO, 2018; Patel *et al.*, 2019). Detecting pollution and toxicity levels in water remains a cumbersome and time-consuming task (Altenburger *et al.*, 2019). Moreover, nutritional deficiencies in juvenile and broodfish populations impede breeding efficiency, while fish health management is hindered by the surge of pathogens and diseases spurred by deteriorating environmental conditions (Sarkar *et al.*, 2022).

To tackle these challenges, an integrated approach leveraging science and technology is imperative for sustaining aquaculture. Among recent developments, nanotechnology has emerged as a promising tool with broad applications in the aquaculture sector (Rodrigues *et al.*, 2017; Samanta *et al.*, 2022). Nanoparticles, characterized by their unique physicochemical properties, offer significant advantages including enhanced reactivity and surface area-to-volume ratio (El-Naggar *et al.*, 2022). Harnessing the potential of nanotechnology holds promise for enhancing efficiency, reducing costs, and mitigating environmental impact in aquaculture systems, addressing the pressing need to sustainably feed the growing global population (Fajardo *et al.*, 2022). In this chapter, we explore the recent advances in nanotechnology and their potential to revolutionize aquaculture and fisheries.

Implementing nanotechnology to enhance sustainability in aquaculture

Nanotechnology has the potential to revolutionize various industries, including aquaculture, by offering innovative solutions for challenges such as water quality management, disease control, and improving feed efficiency. Here are some applications of nanotechnology in aquaculture:

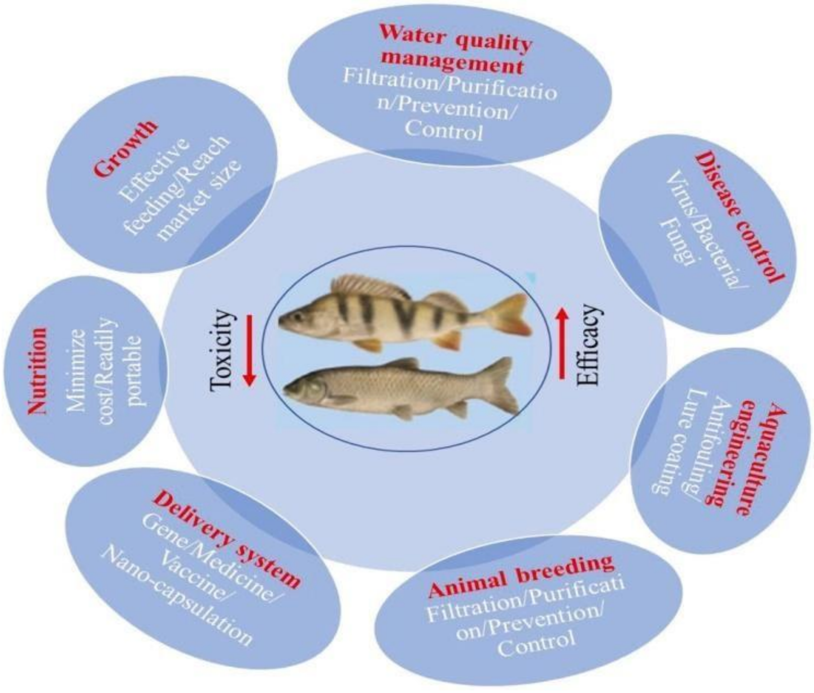

Figure 1: Aquaculture application aspects of nanoparticles (Samanta *et al.*, 2022)

1. Water quality management:

Nanotechnology plays a pivotal role in addressing water pollution, a critical concern in aquaculture due to the increasing disposal of waste materials and misuse of antibiotics and synthetic compounds (Fajardo *et al.,* 2022). Such water degradation not only directly impacts human health but also indirectly affects aquatic life, potentially leading to food-borne illnesses. Additionally, the fishery industry suffers significant economic losses from microorganisms and heavy metal contamination in water, resulting in stunted growth and fish mortality. Nanotechnology offers essential applications in water treatment for creating safe habitats for fish breeding (Shah and Mraz, 2020). Through techniques like photo-catalysis and adsorption using nanomaterials, cost-effective and efficient methods for water purification are being developed (Fajardo *et al.,* 2022). Globally, graphene oxide (GO) and graphene nanosheets (GNs) have gained attention for their efficacy in removing various contaminants from water (Liu *et al.,* 2016; Kuang *et al.,* 2017). Composites like graphene oxide-titanium oxide are utilized for heavy metal and organic compound removal from wastewater (Atchudan *et al.*, 2017). Titanium oxide, known for its non-toxicity, low cost, and efficient photocatalytic properties, shows promise in residual water treatment. Research indicates its ability to eliminate a wide range of pathogens through the production of reactive oxygen radicals and peroxides (Foster *et al.,* 2011).

Nanoparticles also demonstrate potential in degrading antibiotics and breaking down pollutants like polychlorinated biphenyls and dioxins (Majumder and Dash, 2017). Reports indicate elevated levels of heavy metals in marine aquatic animal tissues due to natural and anthropogenic factors (Fajardo *et al.,* 2022). Novel solutions like magnetic konjac glucomannan aerogels have been developed to combat arsenite contamination in groundwater (Ye *et al.,* 2016). In aquaculture, nanomaterials aid in removing contaminants like ammonia, nitrites, and nitrates through aerobic and anaerobic biofilm processes, utilizing activated materials such as carbon or alumina, often with additives like zeolite and iron-containing compounds (Rather *et al.,* 2011). Ultrafine nanoscale iron powder proves effective in cleaning less toxic carbon compounds, thereby advancing nano-aquaculture.

These applications underscore nanotechnology's potential to transform aquaculture, offering sustainable solutions for enhanced productivity, environmental conservation, and fish welfare.

2. Managing diseases in aquaculture:

Addressing disease outbreaks is vital for the sustainable development of aquaculture. Effective management of fish health is essential for preventing and treating pathogenic infestations (Sibaja-Luis *et al.,* 2019; Yang *et al.,* 2021; Fajardo *et al.,* 2022). Nanotechnology offers innovative solutions in disease diagnosis and health management (Handy, 2012).

Nanomaterials serve as drug delivery systems (DDS) and therapeutic tools, offering unique properties such as sustained release, size and shape control, targeted delivery, and regulated degradability (Patra *et al.,* 2018). Additionally, nanoparticles are utilized in gene therapy within the aquaculture sector (Xiang, 2015). For instance, 'Clynav', a DNA vaccine recommended by the European Medicines Agency, protects Atlantic salmon from acute infections. Recent studies have demonstrated efficient carriers like chitosan-dextran sulfate and silica nanoparticles for delivering dsRNA into Penaeus monodon post-larvae, resulting in significant survival rates after gene silencing (Kumar *et al.*, 2016).

Phyto-nano composites, derived from herbal extracts, are emerging as potential treatments for fish diseases. Nanoparticles synthesized from medicinal plants demonstrate antibacterial activity against fish pathogens like Aeromonas hydrophila (Sarkar *et al.,* 2022).

Nanovaccines are gaining prominence in aquaculture as a defense mechanism against pathogens (Ji *et al.,* 2015). Vaccination, whether through oral administration or injection, is crucial for large-scale pisciculture success, particularly in salmon, trout, and Indian major carp farming (FAO, 2018). Over the past two decades, fish vaccinations have proven to be a costeffective method for preventing pathogenic infections (Assefa and Abunna, 2018). Nanovaccines offer a promising mass vaccination approach, overcoming challenges associated with traditional liquid vaccines' storage and administration limitations.

3. Boosting growth performance in aquaculture through nanoparticle supplementation:

Nanoparticles offer promising avenues for enhancing growth performance and bolstering immunity in aquaculture. Studies by Sarkar *et al.,* (2022) indicate that various nanoparticles serve as growth promoters and immunomodulators when incorporated into fish diets on a microscale. This approach, termed nanoparticle nutraceuticals, has emerged as a leading strategy for augmenting aquaculture production (Onuegbu *et al.,* 2018). For example, the supplementation of iron nanoparticles in fish diets has shown significant growth enhancements in sturgeon and carp, with increases of 30% and 24%, respectively (Srinivasan *et al.,* 2016).

Similarly, the addition of selenium nanoparticles to basal diets has demonstrated improvements in weight gain, antioxidant profiles, and muscle bioaccumulation in crucian carp (Wang *et al.,* 2017). Notably, nanoscale selenium exhibits lower toxicity and higher up-regulation of seleno-enzymes compared to metallic selenium (Sarkar *et al.,* 2015a), while also maintaining gill membrane integrity and acting as a chemo-preventive agent (Samanta *et al.,* 2022). Further investigations have revealed that supplementation of various nanoparticles, including zinc, iron, iron oxide, zinc oxide, manganese, copper, silver, magnesium oxide, copper oxide, and chitosanderived nanoparticles, leads to improved fish growth, stress resistance, and bone mineralization, thereby fostering aquaculture development (Moges *et al.,* 2020; Samanta *et al.,* 2022). Optimal supplementation levels can be recommended, such as 20 mg/kg for dietary iron oxide and copper nanoparticles and 5 mg/kg for chitosan-derived nanoparticles (Srinivasan *et al.,* 2016; Samanta *et al.,* 2022).

4. Enhancing seafood processing through nanotechnology:

The necessity to extend the shelf-life of seafood products has driven the exploration of nanotechnology applications in both seafood marketing and aquaculture. Research in food packaging has intensified, utilizing nanomaterials to imbue products with novel properties such as oxygen depletion, reduced enzyme activity, antimicrobial and antifungal capabilities, pathogen and toxin detection, thereby enhancing product stability (Jiang *et al.,* 2015; Kumar *et al.,* 2020; Kuswandi, 2016; Sibaja-Luis *et al.,* 2019). A primary objective of the food industry is to preserve not only freshness but also quality by extending shelf life. Encapsulating essential oils in various nanostructures like nanotubes, polymeric nanoparticles, zein nanoparticles, cyclic oligosaccharides, and other biodegradable nanoparticles has yielded promising results in seafood processing (Abarca *et al.,* 2016; Pavela *et al.,* 2017). Chitosan, employed as a preservative agent in seafood, such as Oreochromis sp., has shown efficacy (Tapilatu *et al.,* 2016). Natural biopolymers such as proteins, polysaccharides, and lipids are utilized to create nanocomposite films.

Recent studies demonstrate that nanoemulsions manufactured with essential oils exhibit antibacterial properties, inhibiting the growth of pathogens like E. coli (Otoni *et al.,* 2014). Lecithin nanoliposomes have been successfully employed to encapsulate essential oils (ValenciaSullca *et al.,* 2016). Stable nanoliposomes containing orange essential oil, created with soy lecithin and rapeseed, were integrated into caseinate starch films (Jiménez *et al.,* 2014). Moreover, organisms like oysters, prawns, and fishes have been utilized for synthesizing nanoparticles, leveraging their rich reserves of bioactive compounds, including minerals, oils, proteins, lipids, flavonoids, vitamins, polyphenols, fibers, polysaccharides (such as fucoidan, laminaran, and alginate), terpenoids, and carotenoids, all of which offer various ethnobotanical functions (Fajardo *et al.,* 2022).

5. Enhancing aquaculture efficiency through biofouling management:

Nanotechnology offers promising avenues for enhancing aquaculture production and shrimp culture by addressing challenges such as disease control, feeding formulation, and biofouling. Biofouling, characterized by unwanted bacterial biofilm as well as the colonization of invertebrates like mussels and barnacles, and algae such as seaweeds and diatoms, can be effectively managed through the application of nanostructures coated or painted with metal oxide nanoparticles like ZnO, CuO, and SiO2. This approach facilitates the creation of highly efficient antifouling surfaces, thereby improving the efficacy of biofouling control methods. These advancements have significant implications, extending to fishing and aquaculture infrastructure, antibacterial treatments for aquaculture tanks, and the development of novel packaging materials for marine products (Nasr-Eldahan *et al.,* 2021).

6. Nanotechnology advancements in fish gonadal maturation and breeding:

Enhancing fish reproduction and breeding is vital for aquaculture, with managing broodstock being a primary step in breeding protocols. Traditionally, achieving gonadal maturation involves administering hormones through injections or feeding supplements, such as human chorionic gonadotropin (HCG), which can induce stress and pain in fish due to handling (Sarkar *et al.,* 2022). To address these challenges, researchers have explored alternative methods like implanting hormonal pellets under the skin (Kailasam *et al.,* 2006). However, nano-encapsulated hormonal delivery has emerged as a more efficient solution, offering slower release and higher retention times (Kumari *et al.,* 2013). By implanting hormone-loaded nanocarriers during the prespawning phase, maturation can be triggered without the need for multiple injections. This approach overcomes the issue of the short lifespan of hormones in the bloodstream, ensuring precise hormone delivery. Additionally, enriching fish feed with essential micro and macronutrients is crucial for developing superior broodstock with high fecundity. Selenium, particularly in nano form, addresses male sterility issues, while phosphorus and calcium supplementation improve female fecundity and egg activation (Sarkar *et al.*, 2015a). Moreover, vitamins and minerals, such as Vitamin E and Vitamin C, play significant roles in enhancing gonadal health, egg quality, and steroidogenesis, further optimizing the breeding process (Volkoff and London, 2018).

Conclusion:

The application of nanotechnology in aquaculture represents a pivotal advancement with transformative potential across various facets of the industry. As global demands for seafood escalate, driven by population growth and dietary shifts, the sustainability and efficiency of aquaculture become increasingly critical. Nanotechnology offers innovative solutions to longstanding challenges such as water quality management, disease control, growth enhancement, seafood processing, biofouling management, and reproductive efficiency. Through nanomaterials like graphene oxide, titanium oxide, and various nanoparticles, significant strides have been made in purifying water, managing diseases through advanced drug delivery systems, and improving growth performance in aquatic species. Nanoparticles have also shown promise in extending the shelf life of seafood products and managing biofouling in aquaculture facilities. Moreover, nano-encapsulated hormonal delivery systems are revolutionizing fish reproduction and breeding protocols, offering precise and effective methods to enhance broodstock quality.

Looking ahead, continued research and development in nanotechnology will be crucial for overcoming environmental challenges, optimizing resource use, and ensuring the sustainable growth of aquaculture. By integrating science and technology, stakeholders in the aquaculture sector can harness the potential of nanotechnology to meet the burgeoning global demand for high-quality seafood while safeguarding aquatic ecosystems and promoting economic prosperity worldwide. Thus, nanotechnology stands poised to reshape the future of aquaculture, paving the way for a more resilient and efficient industry in the face of evolving global needs and challenges.

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IMPACT OF NANOMATERIALS ON NON-TARGET INSECT SPECIES

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Abstract:

The current reliance on heavy doses of fertilizers and pesticides in conventional agriculture has led to adverse effects on living beings and ecosystems. The introduction of nanotechnology in agriculture, while promising to enhance the efficiency of agricultural inputs, also raises concerns about the potential risks to beneficial organisms within the agroecosystem. As the use of nanomaterials expands across various scientific fields, it becomes increasingly urgent to understand their toxic effects on different non-target organism species and the surrounding ecosystem. Recent evidence suggests that nanomaterials when released into the atmosphere, can result in harmful effects not only on aquatic organisms but also on insect species. While extensive research has been conducted on the toxicity of nanomaterials in marine organisms, studies focusing on their impact on insects are still relatively scarce. This underscores the importance and urgency of understanding the impact of nanomaterials on non-target insects in agriculture.

Keywords: Nanotechnology, Agroecosystem, Nanomaterials, Environment, Toxicity.

Introduction:

Nanotechnology refers to technology applied at the nanoscale with real-world applications. It involves manipulating or restructuring matter at the atomic and molecular levels within the size range of approximately 1 to 100 nanometers (Bhushan, 2017). This field is based on the principles of nanoscience. The term "nanotechnology" was introduced by physicist Richard Feynman during a talk at an American Physical Society meeting at Caltech on December 29, 1959.

A nanometer is one billionth of a meter and materials with dimensions smaller than 100 nanometers can be classified as nanomaterials. These nanomaterials can be naturally occurring, engineered or incidentally formed, and they can exist in various forms, such as crystalline, amorphous, polymeric or composite structures. These have different shapes, such as rods, tubes, cones, spheres and fibres. Nanomaterials may be metallic (e.g. ZnO, TiO_2), non-metallic (e.g., carbon), semiconducting (e.g., cadmium, selenium), or in combinations. The properties of materials change significantly at the nanoscale compared to the larger scale. Initially, reducing the size of a material has little effect on its properties, but when the size drops below 100 nm, dramatic changes occur in the properties of materials. Nanomaterials' unique physical and chemical properties can be utilized for commercial applications and innovative performance, providing societal benefits (Bhushan *et al.*, 2014).

Nanotechnology in agriculture

Agriculture is at the heart of human civilization, providing food and livelihoods for billions globally. However, the modern agricultural sector faces numerous challenges, including population growth, climate change, diminishing natural resources and environmental degradation. However, the modern agricultural industry faces innumerable challenges, including population growth, climate change, diminishing natural resources and environmental degradation. With the global demand for food increasing, finding innovative and sustainable solutions to address these issues is essential. Nanotechnology has emerged as a transformative technology with the potential to revolutionize various industries. In agriculture, the adoption of nanotechnology promises a significant shift, enabling more efficient, sustainable and environmentally friendly farming practices (Sahoo, 2024).

Application of nanomaterials in agriculture

Nanomaterials have a wide range of potential applications in agriculture, focusing on enhancing crop productivity and improving soil health. Here, there are various developments in nano fertilizers, nano pesticides, nano biosensors and nano-enabled remediation of contaminated soil (Usman *et al.*, 2018).

A. Nano fertilizers: Nanofertilizers are a recent advancement in agriculture known for their nanoscale size and high surface area to volume ratio, contributing to their enhanced efficiency compared to conventional fertilizers. Various nano fertilizers, such as iron, zinc, silver, titanium, molybdenum, carbon nanotubes and silica, have been developed. These have been applied to various crop systems. The nanoform fertilizers move faster in comparison to conventional fertilizers. Conventional fertilizers typically exhibit low nutrient use efficiency, leading to significant nutrient wastage and environmental pollution (Chhipa, 2019).

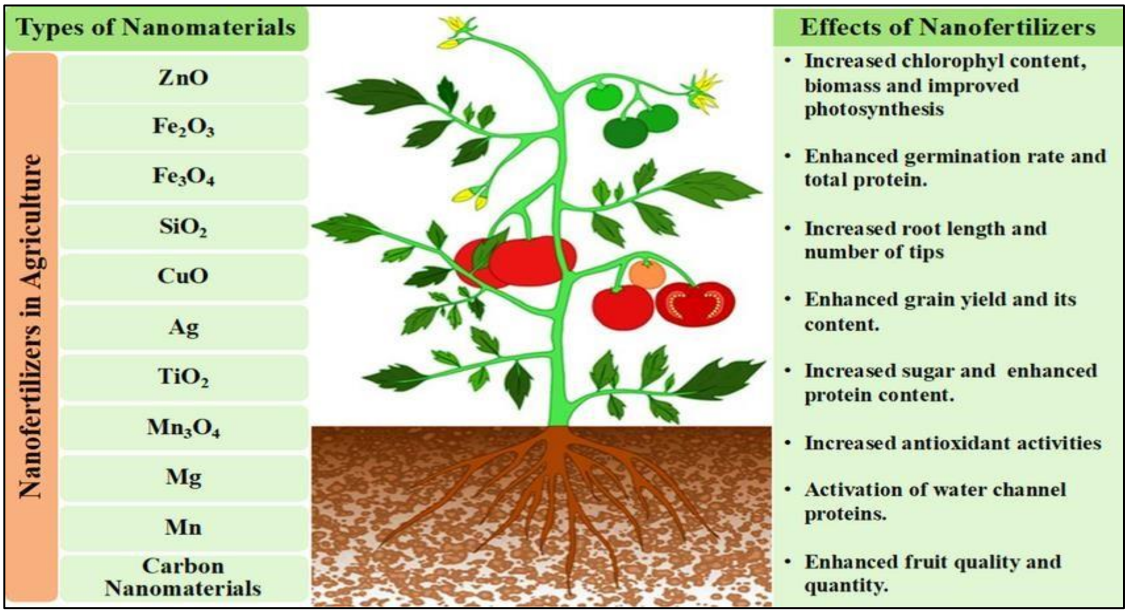

Figure 1: Different nanomaterials used as nanofertilizers and their effects in agriculture (Source: Singh *et al.*, 2022)

B. **Nano-pesticides** represent a new, more efficient category of pesticides, mainly referring to the following two types. The first type involves nano-pesticides whose effective ingredients are nano-sized, including powder pesticides and nano dispersant/(micro) emulsion pesticides. The second type consists of pesticides that are either loaded with, doped in, or directly coated with nanomaterials to put a "nano-coat" on their surface. The nanocomponents in these pesticides enhance the performance of the active ingredients, facilitate targeted delivery, protect the pesticides and control their release. Compared to traditional pesticides, nano-pesticides offer reduced volume usage and increased efficiency (Mohasedat *et al.*, 2018).

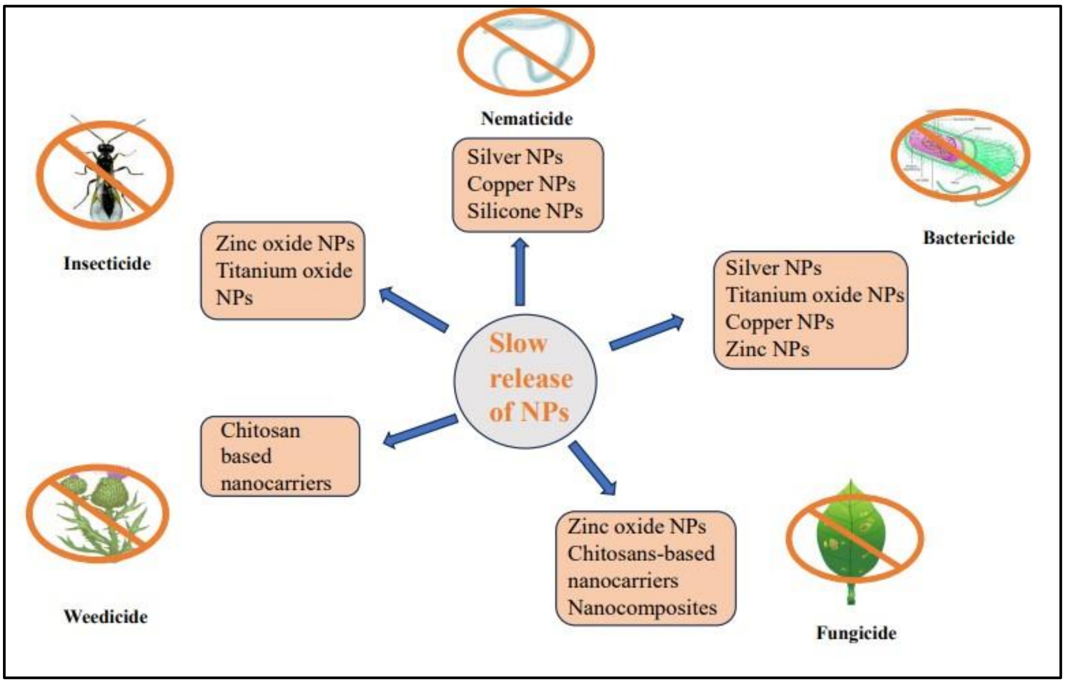

Figure 2: Different types of nanomaterials-based nanopesticides

C. **Nanosensors** are nanoscale devices designed to measure physical quantities and convert them into signals for detection and analysis. Nano biosensors made from nanomaterials are crucial for quantifying various chemical samples and microorganisms, including fungi, bacteria and viruses in plants (Duhan *et al.*, 2017). In real-time, miniaturized optical, magnetic and electrochemical nanosensors monitor soil quality, crop growth environment, plant pathogens, moisture levels, etc. Farmers can quickly respond and implement precision agriculture techniques by utilizing networked nanosensors. MoS_2 (Molybdenum disulfide) based sensors have been extensively reported for detecting heavy metal ions, pesticides, nitrates, and other pollutants (Sha *et al.*, 2020).

Nanoparticles used as insecticides

Nanoparticles are highly effective against insect pests that are sap-sucking and leaffeeding. Various nanomaterials, such as aluminium oxide, nano silica, titanium dioxide, zinc oxide and silver nanoemulsions, developed into insecticides for use in storage and fields. Chandrashekharaiah *et al.*, (2015) reviewed the application and modes of action of nanomaterials in pest management. Nanoparticles applied on the plant as nano fertilizers and nano pesticides get adsorbed into the insect body when the insect crawls over the surface and is absorbed into the cuticular lipids. The peristaltic movements of the insects then facilitate the entry of nanoparticles into their body tissues, causing physical damage to cell organelles.

This results in the oozing of body fluids and leads to desiccation death (Kannan *et al.*, 2020).

Importance of non-target insects

Insects are essential components in the food chain and help maintain ecological balance within the agroecosystem. This group of insects comprises scavengers, predators, parasitoids, pollinators, natural enemies and decomposers. Pollinators such as pollen wasps , honey bees, bumblebees, hoverflies, solitary bees, ants, mosquitoes, butterflies, moths and flower beetles are essential for pollinating crops, aiding seed and fruit production and enhancing agricultural productivity. Insects like soil ants, flies, scavenger beetles, crickets, termites and wasps live in the soil and they make tunnels in soil, which improves soil aeration, earthworm populations and beneficial microorganisms (Kannan *et al.*, 2020). Predators and parasitoids of agriculturally significant insect pests are vital in reducing pest outbreaks.

The potential applications and advantages of nanotechnological tools in pest management have grown significantly in recent years. The possible effects of different nano inputs on these insects in the agricultural ecosystem must be studied thoroughly to minimize negative impacts and preserve them for maintaining ecological balance. (Prasad *et al.*, 2014, 2017a, b; Bhattacharyya *et al.*, 2016).

Non-target insect groups

In agriculture, insects are predators, pollinators and parasitoids, producing valuable products such as honey, silk, and wax.

a) **Insects as predators** - Insects are essential predators, feeding on other insects and helping to control pest populations. Many predatory insect species, such as ladybugs, lacewings and predatory mites, consume pest insects that can damage crops. In the insect orders Neuroptera (lacewings and ant lions) and Odonata (dragonflies), all the species are predators. Additionally, a large percentage of species in the orders Hemiptera (bugs), Hymenoptera (wasps, bees and ants), Coleoptera (beetles) and Diptera (flies) act as predators either during their larval stage or throughout both their larval and adult stages (Jankielsohn, 2018)**.**

b) **Insects as pollinators** - Insects play a crucial role as pollinators, facilitating the transfer of pollen between flowers, which is essential for the fertilization process that leads to seed and fruit production. Approximately 72% of global crops depend on insect pollination (Dicke, 2017). Insect pollinators include hundreds of solitary bees, bumblebees, flies, beetles and butterflies, hoverflies and honeybees. On a global scale, insect pollination services are estimated to contribute 9.5% to crop production yields (Jankielsohn, 2018)**.**

c) **Insects as parasitoids**—Parasitoids are insects that lay their eggs on or within the bodies of other insects, typically a pest species. The larva feeds on the host insect, ultimately leading to its death. Examples of parasitoid insects include wasps, flies, and beetles. Various parasitoids belonging to the order Hymenoptera can parasitize adult insects, larvae, or eggs. The parasitoids are an essential biological tool extensively utilized in agriculture to control various pest species (Kalyanasundaram & Kamala, 2016).

Mechanisms of nanomaterial exposure

- **Direct Contact** - Insects may directly interact with nanomaterials when applied to plants, soil, or water. This interaction can occur through their body surfaces or appendages. The small size of nanomaterials allows them to penetrate biological membrane barriers, causing negative effects. These adverse effects include ions overload and the release of ions that disrupt homeostasis, as well as the retraction of organelles into the cell and increased production of reactive oxygen species (Tuncsoy & Tuncsoy, 2022).
- **Ingestion** - Insects can ingest nanomaterials through contaminated water, food or soil. These nanomaterials can be absorbed by plants and transferred to nectar, pollen or plant tissues, which herbivorous insects consume. Nanomaterial uptake into cells involves clathrin & caveolae-dependent endocytosis, macropinocytosis and clathrin & caveolae-independent endocytosis. Intestinal epithelial cells are tightly joined, with tiny gaps (*i.e.* 0.1 nm) between tight junctions to prevent nanomaterial permeation (Barua & Mitragotri, 2014). For instance, 60–80 nm-sized and 100 nm-sized nanoparticles are taken into the cell by caveolae-mediated endocytosis and clathrin-mediated endocytosis respectively (Tuncsoy & Tuncsoy, 2022).

Impact of nanomaterials on predators –

Dragonflies, damselflies, lacewings, praying mantis, robber flies, giant water bugs, wasps and hoverflies are common predators of insect pests. Exposure to low concentrations of silver nanoparticles (Ag NPs) altered common natural predatory dragonflies behaviour, survival and reproduction (Kannan *et al.*, 2020).

Lacewings are popular, commercially available beneficial insects. These distribute eggs or larvae evenly around infested plants to minimize cannibalism and maximize their usefulness as biological control organisms.

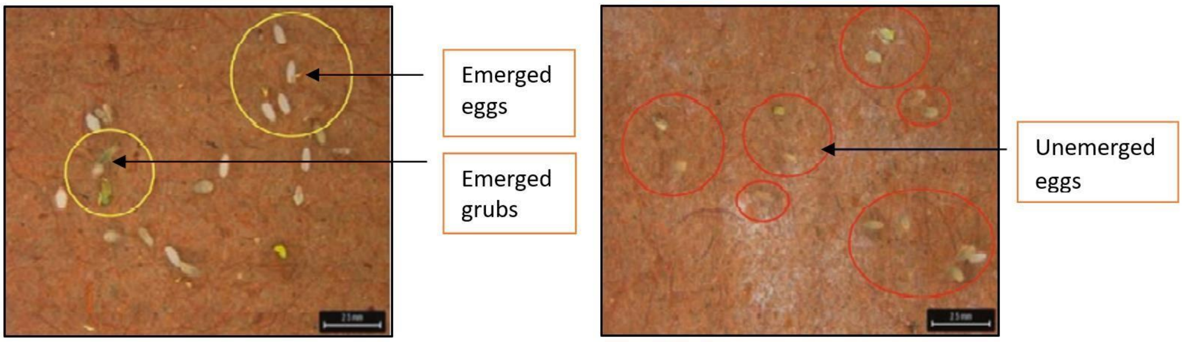

Figure 3: Effect of silica nanoparticles (Si NPs) on the emergence potential of lacewing (Source: Kannan *et al.*, 2020)

The green lacewings are highly effective predators for managing insect pests. Karthika *et al.* (2015) evaluated the safety of hexanal nanoemulsion to the *Chrysoperla carnea* Stephens larvae and found that nanoemulsion was non-toxic, with 100 percent pupation and adult emergence observed. Similarly, Kannan and Elango (2019) investigated the impact of silica nanoparticles (Si NPs) at various concentrations (ranging from 50 ppm to 20,000 ppm) on the egg emergence potential of another green lacewing species, *Chrysoperla zastrowi sillemi* (Esben-Peterson) and discovered that emergence rates were significantly lower at 20000 and 15000 ppm, at 29.41%, compared to 96.51% in the untreated control group.

Impact of nanomaterials on pollinators –

Pollinating insects such as bees or bumblebees have potentially come into contact with nanomaterials *via* aerosols, contaminated plant pollen and water droplets. Managed pollinators might face extra exposure within hives because beekeepers sometimes directly apply nanomaterials. This raises concerns about the risk these insects face due to nanomaterial exposure.

Figure 4: Insect biodiversity on a flower (Source: kathomenden -stock.adobe.com)

Routes of exposure to nanomaterials

Nanomaterials can be released into the air, water bodies, and soil through plant protection products (nano pesticides), fertilizers (nano fertilizers), and remediation agents. The main route of pollinating insect exposure is *via* foraging on nanomaterial-contaminated pollen.

Some of the laboratory studies summarized below enlist the effects of nanomaterials on pollinators.

The study with titanium dioxide nanoparticles (TiO_2 NPs) demonstrated that these nanoparticles decreased the development and moulting duration of *Bombyx mori* (Li, 2014).

Ozkan *et al.*, (2015) conducted the first toxicological evaluation of silver nanoparticles loaded into titanium dioxide (Ag-TiO_2) and TiO_2 and the zinc oxide (ZnO-TiO_2) composite in a honey bee (*Apis mellifera*). The results show no mortality and no behavioural abnormalities in the control groups. Assessment of LC50 values for 96 hours are 5.865 mg/l for TiO_2, 6.315 mg/l for ZnO-TiO_2 and 312.845 mg/l for Ag-TiO_2. The concentration levels that most significantly impacted mortality rates were 100 mg/l for TiO_2, 1 mg/l for ZnO-TiO_2 and 10 mg/l for Ag-TiO_2. The study also showed that the toxicity of TiO2, ZnO-TiO2, and Ag-TiO2 nanoparticles increased with higher concentrations and longer exposure times.

The sizeable annual production and utilization of cerium (IV) oxide nanoparticles ($nCeO_2$s) might result in their release into the atmosphere and considerable deposition on plants, posing a potential risk to pollinators. The effects of $nCeO_2$-spiked food (2–500 mgL^{-1}) on winter and summer honeybees (*Apis mellifera carnica*) over a chronic 9-day oral exposure period. Acetylcholinesterase (AChE) and glutathione S transferase (GST) activities were measured in different body parts (heads, thoraces) and haemolymph. AChE activity was assessed in salt-soluble (SS) and detergent-soluble (DS) fractions. The result showed that exposure of honeybees to $nCeO_2$-spiked food did not significantly affect their survival up to 500mgL^{-1} (Kos *et al.*, 2017).

Impact of nanomaterials on parasitoids –

Trichogrammatidae are very effective egg parasitoids, targeting the eggs of insects belonging to more than eight orders in terrestrial and aquatic habitats. Karthika *et al.*, (2015) found that a nanoemulsion of hexanal at 0.02% exhibited low toxicity to the immature stages of *Trichogramma japonicum* Ashmead, with adult emergence rates ranging from 97.15 to 93.05 percent in different doses. The hexanal treatments had minimal effect on the parasitization rate of *Trichogramma chilonis* Ishii.

Mohan *et al.*, (2017a, b) demonstrated that hexanal nanoemulsion was safer than *Trichogramma pretiosum* Riley and *T. chilonis*, achieving parasitization rates of 98.53% and 97.88% and adult emergence rates of 97.57% and 96.60%, respectively. The secondgeneration adults also showed high parasitization (96.12% for T. *pretiosum* and 97.65% for T. chilonis) and adult emergence (94.29% and 96.40%, respectively).

Preetha *et al.*, (2018) reported that the neem oil-based nanoemulsion was safer for egg parasitoid *T. chilonis* than a macroemulsion. The parasitism and adult emergence rates were significantly higher with the nanoemulsion (86.00% and 79.98%, respectively), while the highest concentration of neem oil macroemulsion resulted in the lowest adult emergence (48.45%) and parasitism (66.78%).

Figure 5: Egg parasitoid: *Trichogramma chilonis* (Source: Kerima *et al.*, 2018)

Kannan and Elango (2019) also studied the effects of silica (Si) nanoparticles at various doses (ranging from 50 to 20,000 ppm) on *T. chilonis* parasitization and adult emergence. They found maximum parasitization in the untreated check (96.69%), with significantly reduced parasitization and adult emergence at 20,000 ppm (16.25% and 19.78%, respectively) and 15,000 ppm (30.41% and 93.48%, respectively) compared to the untreated check.

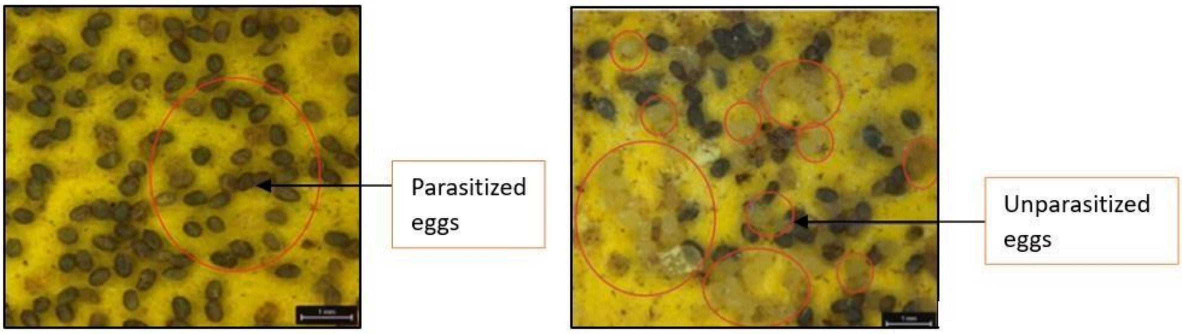

Figure 6: Effect of silica nanoparticle on the parasitization potential of *Trichogramma chilis* Ishii (Source: Kannan *et al.*, 2020)

Bioaccumulation

The bioaccumulation of nanomaterials starts with the accumulation of nanoparticles within an organism, leading to biomagnification in predatory organisms. The final stage is biotransformation, where the toxin concentrations in the organisms exceed those in the environment. This stage involves a bioactivation process that generates more toxic reactive metabolites, increasing these toxic chemicals throughout the food chain (Uddin *et al.*, 2020).

Conclusion;

Nanotechnology is an emerging scientific field capable of resolving issues and problems that are difficult to solve in engineering, agriculture and other biological sciences. With the growing population worldwide, there is an increasing need for agricultural inputs to produce sufficient food cheaply. However, the growing use of pesticides harms farmers, consumers, non-target organisms and the environment. It is essential to understand the impact of nanomaterials on biological parameters, predatory efficiency, parasitism and insect emergence capacity to protect parasitoids, predators, and pollinators from nanotoxicity, which is vital for managing insect pests in the cropping system.

Recent literature on the impacts of nanomaterials on non-target insects, particularly predators, parasitoids and pollinators, reveals that nanomaterials do not harm these insects but significantly reduce their parasitization and adult emergence.

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ENHANCING PLANT NUTRITION WITH NANO-FERTILIZERS

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Abstract:

A novel approach to increasing agricultural or plants yield that is affordable, beneficial to living things, and environmentally safe without sacrificing quality is provided by nanotechnology. The use of environmentally friendly technology to replace traditional agricultural inputs like insecticides and fertilizers is becoming more and more popular. The limitations of traditional agricultural methods can be broken through with the use of nanotechnology. It provided a novel viewpoint on the creation and use of nanoparticles as agricultural herbicides and fertilizers, as well as a means of enhancing bio-factor execution. The use of nano-fertilizers is essential to minimizing the harm that traditional, inorganic fertilizers do to the environment. Due to their increased sensitivity and capacity to permeate the epidermis, nano-fertilizers can reduce nutrient excess and increase nutrient absorption efficiency. The macro- and micronutrients found in nanoparticles, which are used in nano fertilizers, are delivered to rhizosphere of plants in regulated pathway. This chapter explores how plant development is affected by various forms and dosages of nano fertilizers based on nanotechnology. Furthermore, the advantages and limits of nano fertilizers have been examined, as well as the mechanism underlying their absorption are discussed and reviewed together.

Keywords: Nano Fertilizers, Nanoparticles, Nanotechnology, Plants.

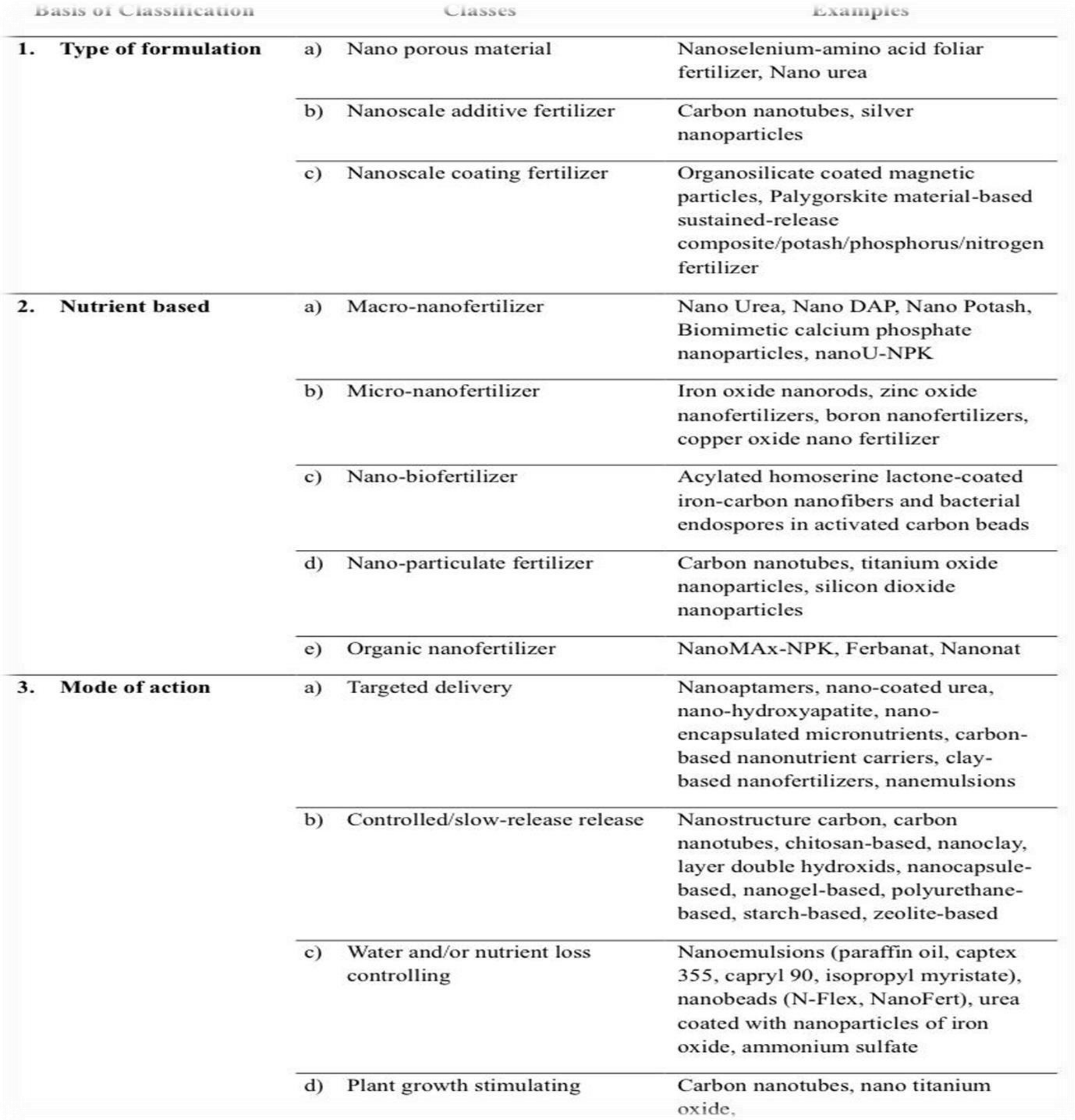
Introduction:

Agriculture is considered to be one of the most vital areas for ensuring food security. Still, as the world's population expands, so will agri-food demands, necessitating a transition from traditional to smart agricultural practices, frequently referred to as agriculture 4.0. Recognizing and addressing the obstacles of agriculture 4.0 is crucial for fully realizing its potential (Singh *et al.*, 2022).It also plays a crucial role in supporting the world's expanding population and propelling its booming economy. In the process, it has become clear that using fertilizers regularly is crucial to maintaining soil fertility and increasing crop yields.

Conventional fertilizers are commonly used to augment vital nutrients in the soil. These include urea, nitrogen, potassium, phosphorous, and di ammonium phosphate. However, leaching causes conventional fertilizers to have low nutrient use efficiency, which results in significant financial losses and diminished soil fertility.

Soil fertility has significantly decreased as a result of these nutrients seeping from the soil. This is mostly because conventional fertilizers have a relatively low nutrient utilization efficiency of about 30–35% for nitrogen and 18–20% for phosphorous (Preetha *et al.*, 2017).In order to outperform conventional fertilizers, nano fertilizers (NFs) are made of materials that are readily available but have low bioavailability, including zinc and phosphorus, and they minimize the loss of mobile nutrients like nitrate to the soil. The agricultural sector has high hopes for the applications of nanotechnologies. Since nanotechnology has significantly revolutionized current science and is expanding at an exponential rate, it and its related applications have become increasingly important in the modern era (Bhardwaj *et al.*, 2022). Particles and materials that are worked at a nanoscale range of 1–100 nm are called nanomaterial (NMs). They can be classified into two categories: those that operate as transporters of macronutrients loaded with nutrients or increased fertilizers, and those that act as nutrients themselves, composed of macronutrients or micronutrients. Because NFs' nanostructure has a high surface-to-volume ratio, which results in more active sites for biological activity, crops can absorb nutrients gradually and sustainably (Mikula *et al.*, 2020).

Table 1: Classification of Nano fertilizers (Mehta *et al.*, 2024)



Basis of Classification	Classes	Examples
1. **Type of formulation**	a) Nano porous material	Nanoselenium-amino acid foliar fertilizer, Nano urea
	b) Nanoscale additive fertilizer	Carbon nanotubes, silver nanoparticles
	c) Nanoscale coating fertilizer	Organosilicate coated magnetic particles, Palygorskite material-based sustained-release composite/potash/phosphorus/nitrogen fertilizer
2. **Nutrient based**	a) Macro-nanofertilizer	Nano Urea, Nano DAP, Nano Potash, Biomimetic calcium phosphate nanoparticles, nanoU-NPK
	b) Micro-nanofertilizer	Iron oxide nanorods, zinc oxide nanofertilizers, boron nanofertilizers, copper oxide nano fertilizer
	c) Nano-biofertilizer	Acylated homoserine lactone-coated iron-carbon nanofibers and bacterial endospores in activated carbon beads
	d) Nano-particulate fertilizer	Carbon nanotubes, titanium oxide nanoparticles, silicon dioxide nanoparticles
	e) Organic nanofertilizer	NanoMAx-NPK, Ferbanat, Nanonat
3. **Mode of action**	a) Targeted delivery	Nanoaptamers, nano-coated urea, nano-hydroxyapatite, nano-encapsulated micronutrients, carbon-based nanonutrient carriers, clay-based nanofertilizers, nanemulsions
	b) Controlled/slow-release release	Nanostructure carbon, carbon nanotubes, chitosan-based, nanoclay, layer double hydroxids, nanocapsule-based, nanogel-based, polyurethane-based, starch-based, zeolite-based
	c) Water and/or nutrient loss controlling	Nanoemulsions (paraffin oil, captex 355, capryl 90, isopropyl myristate), nanobeads (N-Flex, NanoFert), urea coated with nanoparticles of iron oxide, ammonium sulfate
	d) Plant growth stimulating	Carbon nanotubes, nano titanium oxide,

The unique characteristics of nanomaterials when paired with native and customary practices could lead to a plethora of inventive uses in a range of scientific fields, including agriculture, which needs creative approaches to guarantee global food security (Raliya *et al.*, 2018). The current task is to create "smart and sustainable" agricultural innovations that will enable quick crop production.The concept of using nanotechnology to agriculture is not new; in fact, research and applications based on nanotechnology have been highlighted in a number of studies released by US Department of Agriculture, Nano-forum & other organizations (An *et al.,* 2022).With their increased effectiveness and decreased environmental impact, nano fertilizers have come into being as a viable answer to these problems. They can be categorized according to their consistency, activity, and nutrient makeup (Mehta *et al.,* 2024).

Mechanistic perspective on the improvement of crop yield and soil fertility by nano fertilizers:

Because traditional fertilizers have a low absorption efficiency, they have to be used in large volumes. The two main issues with phosphate and nitrogen fertilizers are their low nutrient intake efficiency and their quick conversion into chemical forms which plants cannot use. The increase in eutrophication & the production of harmful greenhouse gases have had a negative impact on soil and ecosystem (Saharan *et al.,* 2018). Nutrients are progressively released using nano fertilizers, which may help increase nutrient use efficiency without having any -ve side effects. The construction of these nano fertilizers ensures environmental safety by reducing nutrient loss significantly and delivering nutrients gradually over an extended period of time (Deshpande *et al.,* 2011). Depending on how they interact with the soil and their nature, the inorganic and organic components of the soil can change the effects of the applied nano fertilizers. Aggregation happens first when soil is treated with nano fertilizers, limiting their area of action. As aggregates get bigger, they become less mobile in porous materials. Therefore, the soil's organic matter content, the environment in which it is placed, and the chemical makeup of the nano fertilizers can all affect how mobile the NPs are. Furthermore, there are numerous ways in which nano fertilizers can affect the activity of soil microorganisms. Nutrition management can benefit from the increased nutrient utilization efficiency that nano fertilizers can provide. When applied either alone or in combination, these nutrients are attached to the nanoabsorbents. NPs are known to exist in soil systems. Researchers have identified a new class of clay particles with a size range of 1-100 nm, dubbed "Nanosols," after closely researching soil. De-novo-synthesized NPs interact with other soil particles vigorousbecause of their unique characteristics, which include a very high specific surface area (SSAs) and tiny subsequent surface charges. Because of their unique qualities, NPs have a very tenacious nature; they do not break down rapidly and they collect slowly in the soil. Frequent application of urea, insecticides, and herbicides is detrimental to the soil's ability to be fertilized. Upon reaching a specific concentration, the behavior of urea, herbicides, and insecticides is comparable (Ghasabkolaei *et al.,* 2017).

Nano-fertilizers production:

Nano fertilizers designed to take advantage of the special qualities of nanoparticles to increase nutrient utilization efficiency. By supplementing nutrients individually or in combination onto the adsorbents with nano-dimension, the nano-fertilizers are created. Nanomaterials are produced using both physical (top-down) and chemical (bottom-up) methods.

The targeted nutrients are loaded as-is for cationic nutrients (NH^{4+}, K^{+}, Ca^{2+}, Mg^{2+}) and after surface modification for anionic nutrients (NO^{3-}, PO_4^{2}-, SO_4^{2}–) (Boopathi *et al.*, 2009).

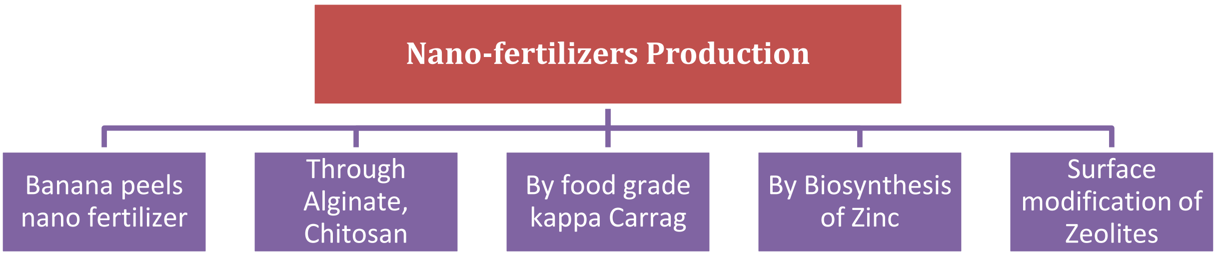


Figure 1: Nano fertilizers Production

One of these novel capabilities is the encapsulation of fertilizers within nanoparticles. This may be accomplished in three ways:

a) The nutrient can be provided as particles or emulsions with dimensions of nanoscales;
b) The nutrient can be covered with a thin polymer film; or
c) The nutrient can be encased inside nano-porous materials (Acharya *et al.*, 2012).

Methods of applying nano fertilizer:

Application of nano fertilizer can be done in three main ways: foliar, seed nano priming, and soil treatment. Foliar application is a technique wherein nano fertilizers are sprayed directly onto plant leaves, facilitating fast nutrient absorption through the leaf surface (Liu *et al.*, 2015). This approach works especially well in areas with poor soil fertility or when nutrients are needed urgently. However, the effectiveness of nitrogen uptake via foliar spray is influenced by environmental conditions such temperature, humidity, and wind (Eichert *et al.*, 2008). Before sowing, seeds should be coated or soaked in a solution containing nano fertilizers, a process known as "seed nano priming". Rapid germination, robust seedlings, and improved nutrient uptake over the course of the plant's life are all encouraged by this strategy. When quick plant establishment is required if the soil quality is low, it is quite helpful. To prevent phytotoxicity, it is necessary to ascertain the ideal concentration of nano fertilizers(Kottegoda *et al.*, 2011). Applying nano fertilizers directly to the soil through banding, disseminating, or localized implantation is known as soil treatment (Subramanian *et al.*, 2015). By guaranteeing a gradual and regulated release of nutrients, the technique lowers nutrient loss due to volatilization or leaching. The optimum places for soil treatment are those with strong nutrient retention capabilities and regular precipitation patterns. But in order to avoid nutritional imbalances or environmental contamination, the application needs to be properly controlled. For plants to develop as best they can, the right kind of nano fertilizer must be applied, and this depends on the soil and climate. Climate, which affects nutrient uptake and utilization, and soil Choosing the right approach after considering these variables can increase crop productivity, lessen environmental effect, and develop more environmentally friendly farming methods. The three application methods are described in full below.

1. Application of foliar spray:

With the use of foliar spray, a cutting-edge technique, liquid fertilizers are directly applied to the leaves or foliage of plants, facilitating the quick uptake of nutrients through the leaf surface.

Table 2: Effect of foliar application of nano fertilizers in different crop and plants

Nanomaterials	Applications	Concentration Used	Mode of Application	Duration of Treatments	Responses	Reference
ZnO	*Cyamposis tetragonoloba*	10 mg	Foliar spray	4-6 weeks	Increase in accumulation of nutrient biomass, and enhanced growth physiology	Raliya *et al.*, 2013
CuO	*Solanum lycopersicum*	15 mg	Foliar	11 days	Eliminated the spread of disease	Giannousi *et al.*, 2013
ZnO, Fe3O4	*Moringa peregrina*	30, 60, 90 mg	Foliar	Watered every 3 days	Salinity levels reduced growth parameters significantly	Soliman *et al.*, 2015
Zn, Fe, NPK	*Chickpea*	20 mg	Foliar	First spraying at 4 to 6 leaf stage, second at 30 days, third during pod filling	Significant increase in both biological and seed output	Drostkar *et al.*, 2016
Zn, BNPs	*Punica granatum*	0, 60, 120 mg	Foliar	Once every season, one week before the first full bloom	Increase in pomegranate fruit yield	Tehranifar *et al.*, 2016
Al2O3 NPs	*Solanum lycopersicum*	400 mg	Foliar	20 days	Effectively counteracts Fusarium as a biocontrol agent	Shenashen *et al.*, 2017

N, P, NPK NPs	*Triticum aestivum*	Not specified	Foliar	Not specified	Significant changes in plant growth parameters like shoot length, root length	Juthery *et al.*, 2019
NPK	*Wheat grains*	500, 60, 400 ppm	Foliar spray	Treatment after 21 days of planting	Significant change in total saccharide content of wheat grains	Hasaneen *et al.*, 2018
ZnO	*Coffea arabica*	15 mg	Foliar spray	40-45 days	Acceleration of net photosynthesis and increased biomass production	Rossi *et al.*, 2019
AgNPs	*Vigna unguiculata*	30-90 mg	Foliar	4-7 days	Growth inhibition of X. axonopodis Pv. malvacearum and other harmful bacteria	Vanti *et al.*, 2018
ZnO	*Triticum aestivum*	40-120 mg	Foliar	Not specified	Enhanced absorption of zinc	Sheoran *et al.*, 2021
ZnO	Rice	25 mg/L	Foliar	Not specified	Increased grain zinc by 55%	Parashar *et al.*, 2023
CuO	Rice	75 mg	Soil	Not specified	Enhanced Cu grain content	Deng *et al.*, 2022
FeO	Wheat	25-100 mg	Soil	Not specified	Increased iron content	Manzoor *et al.*, 2021
Cu	Barley	500 mg	Foliar	Not specified	Twofold increase in Cu grain content	Josko *et al.*, 2023

The technique uses the application of nano fertilizer to the leaf surface to provide precise, optimal, fast, and targeted plant uptake. One promising way to give plants critical materials like fungicides, herbicides, preservatives, and fertilizers is by applying NPs topically. This strategy makes use of delayed release mechanisms to increase these drugs' efficacy. Although the method greatly relies on particle size, foliar-applied NPs can be absorbed through stomata, endocytosis, and direct absorption. Cell walls and leaf wax can function as barriers, preventing these particles from being absorbed. Most NPs settle in vacuoles after being absorbed. However, a number of variables, such as plant traits, NP physical qualities, and environmental circumstances, affect how well NPs are absorbed and transported. In comparison to conventional soil treatments, foliar spraying has a number of benefits, such as a quicker reaction time, better nutrient absorption, and less leaching and runoff (Hong *et al.,* 2021). Numerous studies have shown that using nano fertilizers topically can greatly enhance nutrient uptake, encourage plant growth, and boost crop output. Applying carbon-based NPs and CeO topically enhanced the yield of bitter melon by 28% and wheat by 36.6% (Rubenecia *et al.,* 2014).

2. Nanopriming of seeds: A pre-sowing procedure known as "seed priming" modifies the physiology of seeds to hasten germination and stimulate plant growth and development by controlling metabolic and signaling cascades. The process, which entails soaking seeds in nano fertilizers, has been demonstrated to cut fertilizer application in half while still producing superior outcomes (Caixeta Oliveira *et al.,* 2021). Nano biofertilizers work as growth-promoting hormone-stimulating agents, entering seed pores and spreading throughout, thus promoting germination and development. By reducing reactive oxygen species and controlling plant growth hormones, using nano fertilizer during seed priming boosts seed germination (Kumawat *et al.,* 2023). Additionally, seed priming increases the expression of several genes during germination, especially those linked to plant resilience, which Traditional techniques for seed priming involve the use of water, nutrients, or hormones to break down the seed coat. Advanced seed nano-priming methods, on the other hand, apply nano fertilizers directly to the seed surface, leaving a significant portion that prevents disease penetration. Absorption of nano compounds at the cellular level minimizes input and circumvents molecular interactions, resulting in the generation of extremely resilient seeds with enhanced germination and growth of seedlings, particularly in stressful conditions. According to studies, bean seed priming with chitosan NPs (0.1, 0.2, and 0.3%) for three hours increased the length of the radicle and seed germination. This was followed by a treatment with 100 mM NaCl. When exposed to salt stress, bean seedlings treated with 0.1% chitosan NPs showed considerably higher proline, chlorophyll a, and antioxidant enzyme efficiencies than untreated, salt-stressed seedlings (Zayed *et al.,* 2017). By boosting antioxidants, controlling internal hormone activity in crops, and lowering the production of reactive oxygen species (ROS), nano fertilizers lessen plant stress(Sharma *et al.,* 2023).

3. Soil management: It is possible to apply nano fertilizers to the soil by traditional methods like side-dressing, broadcasting, or fertigation. Once in the soil, the NPs engage in root-related interactions with plants either by adhering to the root surface or by endocytosing root cells

(Ahmed *et al.,* 2021). Nano fertilizers have the ability to interact with soil particles, microbes, and plants in the soil, potentially changing their function and behavior. Plant development and productivity are increased by the regulated release of nutrients from the NPs, which guarantees a constant supply of necessary elements (Madzokere *et al.,* 2021). Although this application approach is thought to be dependable, it has issues with regulators, increased prices, and the unclear long-term effects of nanoparticles.

Table 3: Advantages of nano fertilizers over conventional fertilizers:

Properties	**Nano fertilizers**	**Conventional Fertilizers**
Nutrient uptake efficiency	Increases fertilizer utilization efficiency	Less effective and poorly absorbed by plants
Control release modes	Encapsulation in conjunction with covering of polymer resin, waxes which control release of nutrients	Excessive release in toxicity and undermines ecological balances
Solubility and dispersion of nutrients	Increase solubility and dispersion of insoluble mineral in soil	Less available to plants due to lower solubility
Effective duration of release	Improve and prolong plants nutrients acquisition rate	Nutrients required by plants are lost as insoluble salts during delivery
Low rate of fertilizers needed	Reduce nutrient loss from leaching, runoff	High fertilizer level are lost due to leaching, runoff

Table 4: Effect of different Nanomaterial that influence plant growth

Nanomaterial	**Size (nm)**	**Plants**	**Application**	**Benefits**	**References**
Ag	21-25	Fenugreek, Common bean, *P. deltoides, A. thaliana*	Seed, Foliar	Promote plant growth, Increase seed yield, Enhance root longation	Jasim *et al.,* 2017; El-Batal *et al.,* 2016; Wang *et al.,* 2013a
Au, Carbon (SWCNT)	10-15	Cucumber, Soybean	Seed, Root	Enhance root elongation, Enhance seed germination and cell growth	Lin and Xing, 2007; Lahini *et al.,* 2015
CeO2	25-30	Radish, Tomato	Root, Seed	Increase chlorophyll content, Improve growth and yield	Gui *et al.,* 2017; Wang *et al.,* 2013b

CuO	20-30	Tomato	Root	Increase root length	Singh *et al.*, 2017
		Maize	Root	Enhance maize growth	Adhikari *et al.*, 2016
Fe2O3	10-50	Spinach, Peanut	Root	Increase plant biomass, Increase growth biomass	Rui *et al.*, 2016
FeS	82	Mustard	Foliar	Improve growth and yield	Rawat *et al.*, 2017
In2O3	20-70	A. thaliana	Seed	Improve physiological and molecular response	Lopez-Moreno *et al.*, 2016
MgO	10	Clusterbean	Foliar	Increase fresh biomass and chlorophyll content	Pardhan *et al.*, 2017
MnO	20	Mungbean	Seed	Improve nitrogen uptake and metabolism	Saharan *et al.*, 2016
Nitrogen (HA)	200	Rice	Root	Improve yield	Kottegoda *et al.*, 2017
Phosphorous (Zn induced P)	10-100	Cotton	Root	Increase growth and biomass	Venkatachalam *et al.*, 2017
SiO2	12	Tomato	Seed	Enhance seed germination	Siddiqui and Al-Whaibi, 2017
TiO2	25	Barley	Root	Increase vegetative growth	Marchiol *et al.*, 2016
CuO	42	Tomato	-	Improve fruit quality and antioxidant property	Hernandez *et al.*, 2019
Se	2-20	Bell pepper	-	Increased level of bioactive compounds under salinity stress	Gonzalez-Graceia *et al.*, 2021
ZnO	50	Pea	-	Efficient nutrient transfer	Skiba *et al.*, 2020
FeO	35-45	Sunflower	-	Improve growth under chromium stress	Mohammadi *et al.*, 2020
ZnO	-	Eggplant	-	Reduced drought resistance	Semida *et al.*, 2021

Restrictions and possible hazards associated with the use of nano fertilizers

Notwithstanding the encouraging results, using nano fertilizers has been linked to a number of restrictions and negative outcomes (Iqbal *et al.,* 2015). The majority of research on nano fertilizers has only been done on a limited scale or in laboratories. The disadvantage of applying nano fertilizersfoliar is that they require a big leaf area that can be used, and if the spray concentration is too high, there is a chance of scorching or burning (Achari *et al.,* 2018). They have to be applied at precisely the appropriate moment because weather affects their effectiveness. More research is required on a number of concerns, including lack of size uniformity of the nanoparticles, standardization of the nano formulations, and optimization of foliar applications of nano fertilizers. It is unclear how nutrition affects the environment and the plant's internal transformation when it comes to providing these chemicals in pastures. The question of whether any nano fertilizers survive intact and make their way to consumers through the food chain or if all of them are transformed to ionic forms in the plant and subsequently incorporated into proteins and other metabolites is yet unanswered (kah *et al.,* 2018).

1. Hazards to human health: The possible effects of nano fertilizers on human health are one of the main worries. Owing to their small size, NPs are readily absorbed by organisms, which may be harmful. Research has demonstrated that ingesting nano fertilizers can harm experimental animals' kidneys, liver, and gastrointestinal tracts. Moreover, NPs have the ability to penetrate biological barriers, including the blood-brain barrier, which may result in neurological harm (Atudorei *et al.,* 2004).

2. Hazards to the environment: Contamination of soil, water, and air can result from the discharge of nanoparticles (NPs) into the environment. NPs have the ability to build up in the soil, which could upset soil ecosystems and reduce soil fertility. Additionally, NPs that seep into aquatic environments from the soil may negatively impact aquatic creatures, resulting in bioaccumulation and biomagnification up the food chain. Additional research is necessary to prevent adverse effects related to nanoparticle emission into the environment (Reinsch *et al.,* 2018).

3. Hazards to the ecology: The possible effects of nano fertilizers on creatures that are not intended targets are a significant source of worry. Studies have shown that exposure to nanoparticles (NPs) can have negative impacts on a variety of creatures, such as fish, birds, and insects (Handy *et al.,* 2008). Nano fertilizers have the potential to cause population decreases by interfering with an organism's ability to reproduce, grow, and develop (Baker *et al.,* 2004). It is yet unclear how beneficial microorganisms like mycorrhizal fungi and bacteria that fix nitrogen are affected by nano fertilizers. To assess the possible ecological dangers of applying nano fertilizer, more investigation is required.

Methodical research:

The interplay between NPs' intrinsic and extrinsic characteristics determines how nanomaterials affect plants. According to the research, this interaction is one of the reasons why different findings are seen in the same class of NPs. For instance, rice seed germination was unaffected by the same treatment, but wheat seed germination was enhanced and corn seeds exposed to TiO_2 NPs displayed delayed germination (Ruffini Castiglione *et al.*, 2011). Without a doubt, nano fertilizers provide plant nutrients to the soil precisely and under control, but little is known about what happens to these nanomaterials after they are in the soil. In soil, aggregates of nanomaterials can develop, and the behavior of the nanoparticles (NPs) in these aggregates is influenced by several soil properties such as pH, granularity, organic matter concentration, soil biota, and porosity. Large-sized aggregates can impede the flow of nutrients and minerals over time, compromising their stability. Furthermore, nanotoxicity can develop in the soil and eventually damage plants (Usman, Basavegowda *et al.,* 2021).

Uptake of Nano fertilizers:

It is possible to apply nano fertilizers (NFs) both topically and subsurface. Plants can receive nano fertilizers through their roots or leaves. When NFs are added to the soil, they seep into the roots and reach the aerial plant sections through the xylem. When NFs are applied to leaves, they can be absorbed by the stomata and moved through the phloem to other areas of the plant (Ebbs *et al.,* 2016). In both cases, NFs ought to flow through the pores in the cell wall. In the plant system, only NFs with a diameter of less than 8 nanometers can get past the cell wall and onto the plasma membrane. The application method, crop type, NF content, and soil climate variables all affect how well a fertilizer is absorbed. Furthermore, the anatomy, morphology, and physiology of plants all have a 14 impact of nano fertilizers in agriculture: a futuristic approach 274 following foliar spray on NF penetration and translocation (Corredor *et al.,* 2009). When administered at the ideal level, NFs are absorbed effectively either directly or via apo plastic and symplastic pathways (Qureshi *et al.*, 2018). It is necessary to look into how NFs are transported from the soil to plants and from foliar spray to plants as this information could help determine how effective NFs are. If NFs are applied through the xylem, an irrigation system is the best method; if NFs are transferred via the phloem, foliar spray is advised and suitable (Shukla *et al.*, 2019). Nutrients from NFs release in about 50 days, compared to 10 days from conventional fertilizers (Seleiman *et al.,* 2021). The hydroxyapatite nano polymers that encapsulate urea and progressively release nitrogen into plants are how the N-NFs are made.

A nanohybrid of urea released nitrogen 12 times more slowly than prilled urea (Kottegoda *et al.*, 2017). Nanoscale nitrogen is the component of the IFFCO-patented product Nano urea (liquid). The size of IFFCO nano-urea particles is about 30 nm. Compared to granular urea, this nano urea has a thousand times larger surface area.

Because of its extremely small size and unique surface properties, nano urea is able to permeate plants more readily. When these nanoparticles go within plant systems, they release N in a controlled way. Compared to conventional urea, nano urea has an 80% higher absorption efficiency (Babu *et al.,* 2022). The mode of action of nanoparticles is diverse and can be applied to both foliar and root entrances. Because it is essential for cell wall openings, the size of the NPs directly affects their absorption (Narayanan *et al.,* 2020). A practical soil management solution for cutting back on fertilizer usage is nano fertilizers. In addition, the slow-release technique permits varying applications based on stages of growth.

Future prospect of Nano fertilizer:

Reducing theamount of agrochemicals used in sustainable agriculture is imperative, and developing a plant nutrient system that is both efficient and environmentally benign is key to this goal. The majority of soils in tropical and subtropical regions are acidic, often significantly low in P, and very susceptible to phosphate sorption (Batista *et al.*, 2021). As a result, novel and cutting-edge approaches to boost crop productivity are being created through the application of nanotechnological and nanoengineering methodologies (Verma *et al.*, 2022). Global growth can be aided by enabling a sustainable agricultural supplement, particularly in developing countries with an abundance of natural phosphate rock resources, when phosphate rocks are processed industrially and used appropriately as P supplies.Optimizing land usage, reducing erosion, maintaining soil quality, improving fertilizer recommendations, designing better replacement systems, choosing the best crop genotypes, and exporting manure are some other sustainable options for controlling P use. Instruments that can track crop requirements and assess inter- and intra-crop demand variability are needed in order to modify the amount of product provided to specific plants or crops (Cave *et al.*, 2021). However, it is projected that the cost of agricultural inputs, such as pesticides and fertilizers, will rise sharply due to the limited reserves. Further research is necessary as the use of nanoparticles in delivery systems based on nanotechnology to provide essential nutrients to crops is still in its infancy (Lang *et al.*, 2021).

Conclusion:

Even though the use of these techniques in agriculture is still in its infancy, they have the potential to alter agricultural systems, particularly in light of the issues surrounding the application of manure. Diverse nano fertilizers can significantly increase agricultural output by reducing fertilizer costs and emission risks. Nano fertilizers offer regulated release and targeted dispersion because of their enhanced reactivity, solubility, and cuticle penetration. Moreover, nano fertilizers can improve crop growth, yield, quality, and nutrient usage efficiency by lowering abiotic stress and heavy metal toxicity. Moreover, nano fertilizers can improve crop growth, yield, quality, and nutrient usage efficiency by lowering abiotic stress and heavy metal toxicity.

Novel nanoparticles (NPs) and nanomaterials that serve as carriers of macro- and micronutrients and can increase crop growth and productivity have been created thanks to recent advancements in nanotechnology. Based on available data, the effects of NPs differ depending on the kind of plant and are impacted by their size, shape, concentration, and application method. Crop productivity can be significantly raised once the ideal dosage and plant requirements for nano fertilizers are determined. Greener nano nutrition could be very beneficial for crop plants in the future, especially considering the known nanotoxicological effects of NPs and nanomaterials. In light of this, it is possible to employ green nanomaterials, or NPs, as a source of nutrients for crops, a move that would greatly advance environmentally friendly nano nutrition.

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NANOTECHNOLOGY IN DISEASE MANAGEMENT: PROTECTING CROPS AND YIELD

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Abstract:

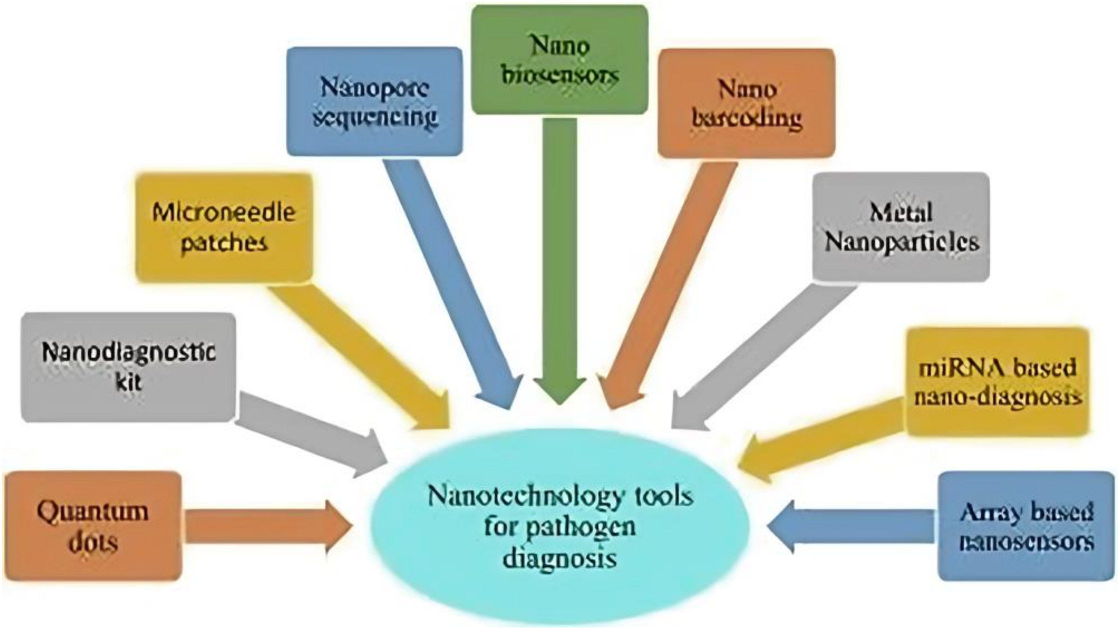
The development of green nano-fertilizers represents a practical strategy in plant disease management through their potential roles in detection, mitigation, and suppression of diseases. Nanotechnology offers a diverse array of tools at the nanoscale, including nanoparticles (NPs), biosensors, nano-diagnostic kits, and advanced fabrication techniques such as nano barcodes and quantum dots. These tools enable precise detection of plant biotic stress through methods like nanopore sequencing systems and microRNA detection. In enhancing plant productivity, nanoformulations and various types of nanoparticles serve as effective nano pesticides. These nanomaterials operate through mechanisms such as the generation of reactive oxygen species (ROS), activation of stress-resistant genes in plants, disruption of pathogen cell membranes, and modification of pathogen DNA. Their integration into agriculture holds promise for optimizing disease management strategies. Overall, the application of nanotechnology in plant disease management emphasizes the strategic use of nanopesticides and nano-fertilizers, showcasing their potential to revolutionize approaches to safeguarding crop health and improving yields sustainably.

Introduction:

Conventional methods often involve heavy pesticide use, leading to environmental concerns and resistance development among pathogens. Nanotechnology offers promising solutions by providing targeted delivery systems and enhanced efficacy of agricultural inputs.

Nanotechnology first applied by Norio Taniguchi in 1974. These small nanoparticles, which often measure less than 100 nanometres in diameter, can perform various tasks at the nanoscale, creating novel possibilities for crop protection that are more efficient and long-lasting. Because of the small size of nanoparticles, they have some unique characteristics, including greater strength, increased heat resistance, lower melting point, and distinct magnetic properties for nano-clusters. They also have higher charge density and reactivity. The atomic distribution of individual nanoparticles differs due to variations in their exposed surfaces, and this variation impacts the kinetics of electron transfer between metal nanoparticles and their corresponding adsorbed species (Schroeder *et al.*, 2013; Naithani *et al.*, 2016).

Nanoparticles, such as silver nanoparticles, have shown potent antimicrobial properties against a wide range of plant pathogens. These nanoparticles can be engineered to encapsulate pesticides, facilitating controlled release and prolonged activity. This approach reduces the quantity of pesticides needed while improving their effectiveness and minimizing environmental impact. Nanotechnology enables precise delivery of agricultural inputs, such as nutrients and bioactive compounds, directly to plant cells. Nanoencapsulation techniques ensure that these materials reach their targets efficiently and are protected from degradation. This enhances nutrient uptake and strengthens plant defenses against diseases. Nanosensors can detect specific pathogens or markers of plant stress with high sensitivity and specificity. Early detection allows for prompt intervention, preventing disease outbreaks and minimizing crop losses. Nanotechnology also contributes to soil health improvement by enhancing nutrient availability and remediation of contaminants. Nano-fertilizers release nutrients gradually, reducing leaching and enhancing nutrient uptake by plants. This approach promotes healthier plants with improved disease resistance and higher yields. Nanotechnology is transforming the agricultural sector by offering innovative solutions to crop disease management.



Different methods of nanotechnology is used for plant pathogen detection

Plant pathogen detection system using the nanotechnology:

Numerous novel methods for plant pathogen detection were rendered likely by nanotechnology, which offers quick, accurate, and targeted ways to identify and track pathogens in agricultural environments. Over the years, various sensing techniques—from the most basic detection of symptoms appearing on leaves to nucleic acid detection approaches—have been used to develop responsive and selective detection systems. The two primary categories of conventional analytical techniques for detecting plant diseases are direct and indirect detection methods. Indirect methods that include hyperspectral imaging, fluorescence imaging, gas chromatography, and thermography are non-invasive techniques (Patel *et al.,* 2022). Direct methods have limited application outside of labs, even though they yield results with high sensitivity and throughput analysis. Sampling preparations are time-consuming, and measurement and analysis must be performed by qualified personnel. Biosensors' high signal-to-noise ratio makes them essential for precisely and efficiently identifying molecules. One of its limitations for its practical and sensitive detection is its instability and weak signal. Combined with the sensor's bio-recognition component, functional nanoparticles that get around these restrictions may improve the device's overall efficiency. Advances in nanotechnology and nanosensors for plant monitoring have led to the use of nanomaterials. Because of quantum confinement, nanomaterials are arranged to be between 1 and 100 nm in size in at least one dimension. They also exhibit unusual qualities like extremely low photobleaching, fluorescence in living tissue on low or transparent backgrounds, and unique magnetic/optical properties. Biosensors have benefited from the use of nanomaterials. High stability, selectivity, fast dynamics, sensitivity, and reproducibility in plant pathogen detection have been attained by the customized size tuning of these nanomaterials in biosensors (Giraldo *et al.,* 2019). Because of their higher surface-to-volume ratio, nanomaterials have been used in biosensors to improve surface contact and the substance being studied.

1. Nano-fertilizers

A specific kind of fertilizer called nanofertilizers utilizes nanotechnology to improve the uptake, delivery, and efficiency of nutrients in plants. Usually, they are made up of micronutrients like zinc, iron, and copper, as well as essential nutrients like potassium, phosphorus, and nitrogen in the form of nanoparticles. These nanoparticles are intended to lessen environmental pollution, decrease nutrient leaching, and increase plant nutrient availability. There are several ways to apply nano fertilizers, such as irrigation, foliar spraying, seed coating, and soil application. Their nanoparticles enable greater penetration into plant tissues, which enhances plants' uptake and utilization of nutrients. Nanofertilizers are not explicitly used for pathogen detection in plants.

- **Enhanced plant health:**

By more effectively supplying vital nutrients, nano fertilizers can improve the vigor and health of plants. Healthy plants are less prone to infections because they are frequently better able to withstand and respond to pathogen attacks. Lowering the frequency and severity of illnesses indirectly aids in the detection of pathogens by making it more straightforward to recognize aberrant symptoms linked to pathogen infection.

- **Modulation of the stress response:**

Plant stress responses, such as those brought on by pathogen invasions, can be regulated through nanofertilizers. Alternating gene expression patterns or biochemical markers can boost the expression of genes linked to defence and stimulate plant immune responses, which may aid in the early detection of pathogen invasion.

- **Nanoparticle-based sensors:**

While not precisely nanofertilizers, nanoparticles can be designed to function as plant pathogen detectors. Specific ligands or antibodies can functionalize these nanoparticles by attaching them to pathogen-specific molecules or biomarkers. The pathogen leads the nanoparticles to exhibit observable changes in their characteristics, such as color or fluorescence, which can be used to identify the pathogen. These nanoparticles can be applied with nano fertilizers using the exact delivery mechanisms, even though they are not directly related to fertilization.

2. Nanocomposites materials:

To boost nutrient use efficiency, these bind fertilizer nutrients into pellets. According to field tests conducted by the Brazilian Agricultural Research Corporation (EMBRAPA), urea and a nanocomposite polymer reduced nitrous oxide emissions by more than 50% (Pereira *et al.*, 2015). The following are a few nanocomposite polymers that can be utilized in fertilizers:

- **PCL, or Polycaprolactone:**

Its technical advantage is that it degrades slowly when broken down by microorganisms like fungi and bacteria. It is also inexpensive and simple to manufacture. The preferred polymer for slow drug delivery in implanted medical devices is PCL; researchers can investigate this feature by using PCL to aid in the slow release of nutrients in fertilizer.

- **Polyacrylamide hydrogel:**

Enhancing montmorillonite's ability to hold onto water can be integrated into pelletized fertilizers, which can reduce the total amount of water required for landscape gardening. However, when the polymer breaks down, lethal neurotoxins and carcinogens called acrylamide are released, which may damage microscopic soil engineers like fungi, bacteria, and protozoa. In addition, acrylamide poses a severe risk to farmers and workers in the fertilizer manufacturing industry as it can be absorbed through the skin or inhaled.

- **Hydroxyapatite Nanoparticle (HANP):**

Hydroxyapatite is a bioceramic compound used in medicine to supply bone and other hard tissues with calcium, phosphate, and other minerals. Because urea and HA have chemical bonds that slow down nitrogen release, urea coated with HANPs increases urea uptake by the plant. The yield of 7.9 tons/hectare can be maintained in farm field trials using ureaHA NP hybrids by reducing urea use by about 50%. This yield is higher than 7.3 tons/hectare for urea-only rice crops using the recommended urea levels (Kottegoda *et al.*, 2017).

3. Nano-biosensors:

It has been demonstrated that nanosensors possess peculiar physical, chemical, and biological properties that are entirely lacking in bulk molecules or their naturally occurring pure form. Strong affinity for their targets, especially proteins, and increased reactivity and physical activity were made possible by the high surface-to-volume ratio of the nanoparticles. With the aid of sensitive electrochemical sensors, compounds indicative of disease conditions, such as salicylic acid, methyl jasmonate, and jasmonic acid, can be detected using nanoparticle-based sensors. Numerous metallic nanoformulations have been created, and it has been discovered that various microorganisms produce nanoparticles in substrates (Andleeb Zehra *et al.,* 2021).

Biosensors at the nanoscale are incorporated into fertilizers' biopolymer coatings so that nutrients are released precisely when needed in response to chemical cues from soil microorganisms like rhizobium in plant roots. A Canadian study team proposed using nanotechnology as an "intelligent nano-fertilizer" in 2012 to give plants more control over the release of nutrients. The application is predicated on the finding that roots release chemical signals in reaction to reduced soil nitrogen. To increase macronutrient uptake efficiency, the Intelligent Nano-Fertilizer project has refocused its efforts from incorporating a nano-biosensor in a polymer coating fertilizer to release urea to putting nano-biosensors in a polymer that coats micronutrients like iron and zinc. Synthetic DNA aptamers have been chosen for this project as nano-biosensors because they fold into unusual three-dimensional structures and can bind tightly to a target—in this case, chemical signals from soil microbes in a plant's rhizosphere (Qureshi *et al.,* 2018). When the aptamer binds to the target, the polymer becomes more permeable and delivers a payload of nutrients. Because misidentification can result in insufficient nutrient release, nano-biosensors must accurately identify specific signals by aptamer between the soil microbes and plant rhizosphere (Neethirajan *et al.,* 2018). Furthermore, the effect of target binding on the properties of the polymer would cause the polymer to degrade, releasing the nutrient incoherently; if a polymer intended to be permeable in response to the rhizosphere, the chemical signal becomes less permeable or even impermeable. Partial or inaccurate delivery of nutrients can result from an aptamer that misinterprets the chemical signal and binds incompletely with the target due to impurities in the nutrient payload.

4. Nano-clays:

To produce soil micro-structures, it lessens nitrate-loaded runoff and stops the release of ammonia and nitrous oxide. These are added to the soil samples. The loss control urea (LCU), a ternary system consisting of attapulgite (nano-clay), polyacrylamide, and urea, which has the highest nitrogen content of all commonly used fertilizers, is one of the best examples of using nano-clays (Cai *et al.,* 2014). In clay-containing soils, adding polyacrylamide and the oxidation and hydrothermal processing of attapulgite increases the pore space and inhibits water runoff and erosion. Water-soluble polyacrylamide is utilized as a soil conditioner. Without polyacrylamide, attapulgite rods (20–50 nm in diameter and 1 μ in length) would clump together and inhibit micro-structure formation that would minimize nitrogen loss. This loss-control technology can reduce nitrogen surface runoff by 45 per cent (Cai *et al.,* 2014).

5. Nano-pesticides:

Due to their being in the form of nanoparticles, nanopesticides are readily absorbed by plants and can be designed to be released over a specific period (Lauterwasser 2005). The following categories are typically used to categorize nano pesticide formulations based on their intended use: Formulations Designed to Improve Poorly Water-Soluble Compounds' Solubility By creating their nanoparticles with a simultaneous change in solid structure, poorly water-soluble active ingredients can appear more soluble, increasing their bioavailability (Horn and Rieger 2001).

Some of the standard pesticide formulations for poor water-soluble active ingredients are as follows:

- **Emulsifiable concentrates (ECs):**

To enable spontaneous emulsification into the water in the spray tank, these concentrates are made up of a combination of surfactant emulsifiers and active ingredients dissolved in an organic solvent. The primary drawbacks of ECs pertain to their comparatively low stability following dilution (droplets of approximately 10 μm) and their utilization of organic solvents, resulting in elevated expenses and flammability, along with increased dermal toxicity for the workers handling those (Knowles, 2005).

- **Oil-in-water (O/W) emulsions:**

O/W emulsions have been suggested as EC substitutes. Block polymers, polymeric surfactants, and a non-ionic surfactant are typically combined to create O/W emulsions. The drawback of O/W emulsion is that emulsification needs a high energy input, which can be obtained from high-pressure valve homogenizers (which produce droplets as small as 500 nm) or high shear mixers (which generally have droplets of 2 μm diameter) (Knowles, 2005).

- **Micro-emulsions:**

These are water-based formulations that are thermodynamically stable and comprise the following components: (a) water, (b) blends of surfactant solubilizers, (c) a co-surfactant, usually medium chain aliphatic alcohol, and (d) dissolved active ingredients in oil (Knowles, 2005; Lawrence and Warisnoicharoen 2006; Green and Beestman 2007). Unlike classical emulsions, which require a significant energy input during preparation, micro-emulsions form spontaneously upon adding water and gentle stirring once the formulation design is established (Lawrence and Warisnoicharoen 2006; Pratap and Bhowmick 2008). According to various reports, the diameters of micro-emulsion particles may be less than 100 nm, and they may be roughly 250 times smaller than those of typical pesticides (Knowles, 2005; ObservatoryNano, 2010). The microstructure of microemulsions can be ascertained by light, neutron, and X-ray scattering methods and pulsed field gradient nuclear magnetic resonance (Lawrence and Warisnoicharoen, 2006). Micro-emulsions are commercially available under various trade names, such as Apron MAXX S. T. Salam *et al.*, 5 (disease protection for soybean; ObservatoryNano, 2010), Banner MAXX (systemic fungicide for broad-spectrum disease control in turf and ornamentals), and Primo MAXX (plant growth regulator). The following are some of the benefits that micro-emulsions have over other formulations, such as ECs: lower flammability because of low solvent content in a continuous water phase; better tank mix compatibility; increased stability; less wear on equipment (e.g., preventing clogged spray tank filters); and increased herbicidal efficacy as a result of the active ingredients better penetration or uptake, which is brought about by surfactants' strong solubilizing power (Knowles, 2005; Green & Beestman, 2007).

6. Polymer-based formulations:

The majority of polymer-based nano-formulations have the controlled release of active ingredients as a primary objective. Polymer-based nano-formulations can be used either as polymeric nano-spheres in which the distribution of active ingredients is not specified or as nano-capsules that exhibit a core-shell structure that can act as a reservoir for active ingredients dissolved in a polar or nonpolar solvent (Anton *et al.,* 2008). Nano-capsules may present advantages over larger capsules in the stability of the spraying solution, increased uptake, increased spraying surface, and reduced phytotoxicity owing to a more homogeneous distribution. However, it is a great challenge to design capsules in the low nm size range while keeping the amount of active ingredients sufficiently high relative to the amount of polymer forming the core-shell structure. (Boehm *et al.,* 2000) compared the properties of nano-spheres prepared with various amounts of poly (epsilon-caprolactone) to improve the delivery to plants.

The release of the active ingredients was immediate and followed a release profile similar to that of a classical suspension. (Boehm *et al.,* 2003) later tested the efficacy of similar nano-spheres loaded with insecticide (average particle size of 135 nm and 3.5% loading rate) on cotton plants infested with aphids. The speed of action and sustained release showed no improvement over a classical suspension, but the small size of the nano-spheres was shown to enhance the penetration of active ingredients in the plants and, consequently, to improve the active ingredients. (Liu *et al.,* 2008) reported a method to produce polymer-stabilized bifenthrin nanoparticles using a multi-inlet vortex mixer to reach high super-saturation followed by rapid nucleation and growth of nanoparticles (named the flash nano-precipitation process). The authors claimed that this preparation method could be scaled up to produce formulations with the potential to provide higher efficiency, better uniformity of coverage for highly active compounds, and reduced exposure to workers relative to compounds solubilized in organic solvents. (Kumar *et al.,* 2010) and (Shakil *et al.,* 2010) recently proposed a self-assembly preparation method using polyethylene glycol (PEG) and various copolymers for the controlled release of insecticides. The diffusion-controlled release rate of active ingredients could be adjusted by changing the proportions and molecular weights of the polymers. Several studies have also proposed using polymeric nano-spheres to release various fungicides for treating wood using conventional pressure treatment methods (Liu *et al.,* 2001, 2002a, b, c; Salma *et al.,* 2010). Polymer nanoparticles can serve as a protective reservoir and diffusion control diffusioncontrolled release carrier. The biocide can thus be released at the minimum rate required to protect the wood, which results in more extended protection and a reduction in losses due to leaching. (Salma *et al.,* 2010) recently reported the development of a novel approach aiming to tackle the weaknesses of the previously developed formulations (by providing lower-cost ingredients, a single preparation step, and optimization of delivery and release rates). Amphiphilic copolymers of gelatin grafted with methyl methacrylate were used to prepare nanoparticles of approximately 100 nm diameter loaded with tebuconazole. The leaching of active ingredients was significantly reduced, and antifungal activity was preserved for more extended periods. However, the novel formulation also exhibited significant aggregation, resulting in less efficient delivery. Regarding pesticide activity, most formulations tested provide adequate protection against fungal attack at relatively low application rates. The surfactant-free formulations exhibited slightly greater biocidal efficacy, possibly due to slower release, reduced leaching (Salma *et al.,* 2010), and more uniform distribution within the wood (Liu *et al.,* 2002c).

Challenges and future outlook:

The complex mechanisms underlying plant-pathogen interactions still need to be understood. It can take much work to thoroughly understand these interactions at the molecular level, which is necessary for developing nanotechnology-based solutions. A significant challenge is ensuring the efficient delivery of nanomaterials to plant tissues or cells while protecting their stability and bioactivity. Optimization is required for efficiency-based strategies like targeted delivery systems and surface modification. A thorough evaluation is necessary to determine nanomaterials' environmental fate and potential ecological effects in agricultural ecosystems. Concerns regarding the accumulation, persistence, and toxicity of nanoparticles in soil, water, and non-target organisms need to be addressed to reduce unforeseen environmental effects. The regulatory frameworks in place may need to sufficiently address the unique qualities and possible hazards connected with nanotechnology in agriculture. To ensure responsible innovation, it is imperative to develop suitable regulations and guidelines for the safe development, use, and disposal of nanomaterials. Plant disease resistance strategies based on nanotechnology may need to be more widely adopted because of their high cost, especially for small-scale farmers in developing nations. Fair agricultural development depends on initiatives to lower production costs and make these technologies more widely available.

Future outlook:

With the help of nanotechnology, plant diseases could be managed with greater precision and focus, lowering the need for broad-spectrum pesticides and their adverse environmental effects. Plant pathogens can be controlled more precisely and successfully in the future thanks to developments in nanomaterial design and delivery systems. Combining nanotechnology with sustainable farming methods like integrated pest management and organic farming could promote green crop protection techniques. Solutions based on nanotechnology can reduce dependency on synthetic chemicals while increasing the resilience of agricultural systems. With the help of nanotechnology, plant diseases could be managed with greater precision and focus, lowering the need for broad-spectrum pesticides and their adverse environmental effects. Plant pathogens can be controlled more precisely and successfully in the future thanks to developments in nanomaterial design and delivery systems. Combining nanotechnology with sustainable farming methods like integrated pest management and organic farming could promote green crop protection techniques. Solutions based on nanotechnology can reduce dependency on synthetic chemicals while increasing the resilience of agricultural systems.

Conclusion:

Improved plant resistance to diseases via the application of nanotechnology offers an intriguing approach to tackling global agricultural challenges. Researchers have shown remarkable capabilities in enhancing plant immunity against pathogens using precise nanoscale material manipulation. Targeted and regulated release of bioactive compounds is made possible by nanoparticle delivery systems, which maximizes efficacy while reducing environmental impact. Additionally, nanomaterials provide platforms for advanced evaluation that make it possible to quickly and accurately identify pathogens so that prompt action can be taken. More research is necessary to completely comprehend nanotechnology's ecological ramifications and long-term effects on agriculture. To ensure the responsible development and application of nanotechnological ways for sustainable crop protection, working together among scientists, legislators, and stakeholders is essential. Ultimately, using nanotechnology to its full potential has enormous potential to protect the world's food supply and foster resilient agricultural systems in the face of changing disease threats.

Employing nanotechnology to increase plant resistance to disease will continue to push the envelope in the future, focusing on ecological responsibility, preciseness, and sustainability. Multidisciplinary research collaborations will be essential for converting fundamental conclusions into practical solutions for global agriculture's intricate problems.

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AQUAPONICS: AN INTEGRATED FISH AND PLANT FARMING

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Abstract:

Aquaponics is an integrated recirculating system that can produce plants and fish together. The basic principle is to efficiently use of water for production of two crops and share nutrient resources between plants and fish. In an aquaponic system, plants and animals have a symbiotic relationship with each other. This chapter provides the concept of aquaponics, including the nitrogen cycle as well as the three main methods of aquaponic systems including media beds, nutrient film technique, and deep-water culture. It also presents details on fish health management, water quality parameters and guidelines and considerations for establishing aquaponic units.

Keywords: Aquaponics, Recirculating, Integrated, Symbiotic.

Introduction:

Aquaponics is a sustainable method of cultivation of fish and plants together in a constructed, recirculating ecosystem. There are many designs of these modern systems treat water to remove any toxic waste products and then reuse it. In this process the fish wastes are removed from the water, first by using a mechanical filter that removes the solid waste and then using a biofilter that processes the dissolved wastes. The nitrate and other nutrients presented in water these travel through grow beds of plant afterward these nutrients uptake by the plants, and last of all the purified water come back to the fish tank. This process allows the plants, fish and bacteria to grow well mutually and to work closely for each other helps to provide that the system is properly balanced (FAO, 2014). This is where the hydroponic aspect of aquaponic systems becomes essential. This system is extremely beneficial to overall crop health and yield because aquaculture wastewater is rich in nitrogen and many other secondary elements that are essential to plant growth (Rakocy *et al.*, 2006).

Due to sustainable nature of aquaponics, it has the potential to develop the food production industry. Now a days various systems of food production like plant production and fish farming, bring negative environmental impacts, including pollution, production of greenhouse gases and soil erosion (Konig *et al.*, 2016). Aquaponics is extremely sustainable, multipart production of food technology that is valued in a progressively urbanized areas where food insecurity and lack of natural spaces are becoming bigger problems every day. (Konig *et al.*, 2016). For these problems aquaponics can be a viable solution that is commonly used in urban and rural areas to raise both fish and vegetable in an integrated system that allow for the highly intensive production of fresh, high-quality food with low water usage and little impact on the environment or biodiversity (Konig *et al.*, 2016).

Role of the nitrogen cycle in an aquaponics:

Nitrogen is a necessary nutrient for plant growth and is rich in a healthy aquaponics system. Nitrifying bacteria transform ammonia and ammonium that found in fish waste (which is toxic for fish) ammonia convert into nitrates, form of nitrogen, a more accessible nutrient that plants can utilize as fertilizer. In an aquaponics system, there are two main types of bacteria and three forms of nitrogen you will find:

Forms of Nitrogen:	Bacteria:
1. Ammonia/Ammonium	1. Nitrosomonas
2. Nitrites	2. Nitrospira
3. Nitrates	

Bacteria of the first set basically consumes the ammonia/ammonium that generate from fish and transform it into nitrite. Bacteria of the second set consumes the nitrites and produces nitrates; it is the most available form of nitrogen for rapid plant growth (ECOLIFE Conservation 2017).

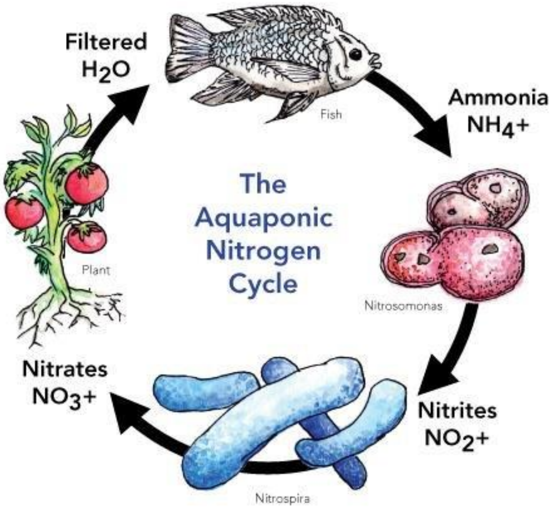

Figure 1: The Aquaponic Nitrogen Cycle

Methods of aquaponic system:

Aquaponic systems can differ greatly in their design and structure, each system type contains certain characteristics. The three most common methods include in aquaponic system are Media Beds, Nutrient Film Technique (NFT), and Deep-Water Culture (DWC).

1. **The media bed technique:**
   Media-filled bed design is the most common system for small-scale aquaponics. This method is user-friendly and usually well suited for hobbyists and home gardeners and strongly recommended for most developing regions. Media Beds are effectual with space, have a comparatively low initial cost and easiest systems to build and maintain as they are relatively simple. Media beds can be construct from fibreglass, plastic, or a wooden frame with polyethylene sheeting or water-tight rubber on the base and inside the walls. In media bed method, the medium is used to helps the plants roots as well as the same

medium functions as a filter, both mechanical (functions as a filter for organisms, parasites, and older solid waste materials) and biological (provides excellent surface area for the required biofilter to grow, which helps reduce ammonia-waste) (FAO, 2014). The plant media is regularly whispered in large containers or grow beds; a separate fish tank is required, and the water from fish tank is pumped or drained into the grow beds (Timmons, 2010). The plants have direct access to water, also the media regularly holds onto water longer, which make sure that plants have abundant time to absorb necessary nutrients (Timmons, 2010). Double filtration helps to the water is purified and then drained back into the fish tank. This system is run predominantly through flooding and draining the grow beds with water by using a bell siphon to automatically drain the water when it reaches a definite soaking point in the media bed (FAO, 2014).

Figure 2: The Media Bed Technique

2. **Nutrient Film Technique (NFT):**

The NFT is a hydroponic growing technique using horizontal pipes each containing a shallow stream of nutrient-rich aquaponic water flowing through it. Plants are grown in the top of the pipes within small holes, and capable to use this thin sheet contain nutrient-rich water (FAO, 2014). If possible, use a rectangular section pipe with larger width than height, which is standard amongst hydroponic growers. A pump sends a constant water with thin stream into the bottom of each channel, where it runs above the plant roots (Timmons, 2010). This offers the plant roots using adequate levels of water, oxygen and nutrients. When the water reaches to the end of the channel, it runs back into the fish tank through a downward channel caused by a small incline (Timmons, 2010). The pipes can be put in many patterns is one of the advantages of the NFT. This technique is more difficult and costly than media beds, and cannot be suitable in locations with insufficient access to suppliers (FAO, 2014). This system is most suitable in urban uses, particularly while make use of vertical space or weight-limitations are deliberations. The NFT system have need of a separate filtration system to clean the water of fish waster or any solids before it go into the channels (Timmons, 2010). If not, the waste can build up, and the roots can be clogged from getting oxygen. The NFT system also needs a further biofiltration component because the system does not have sufficient surface area to support a colony of bacteria that is necessary to system health (Timmons, 2010).

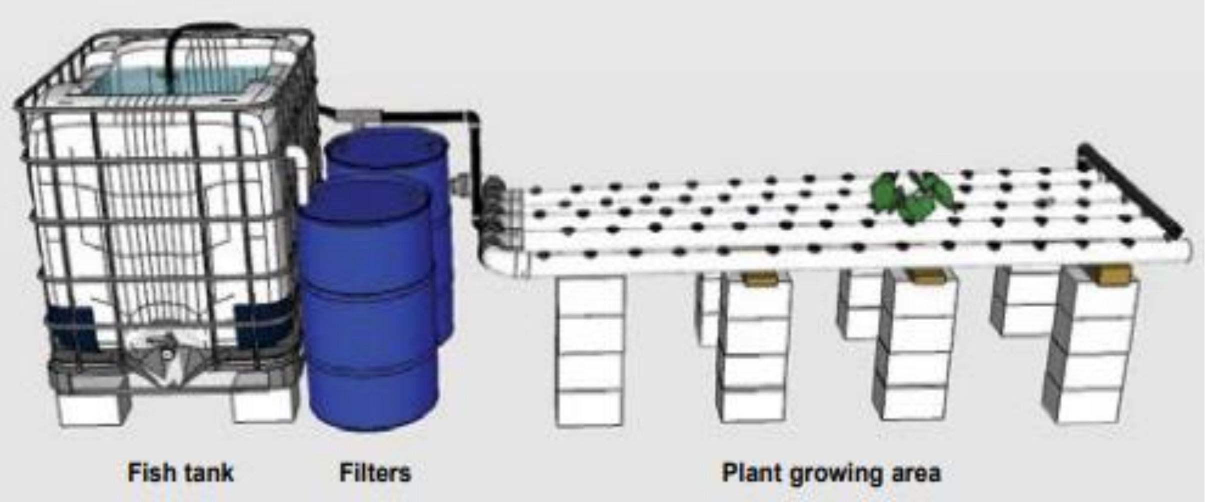

Figure 3: Nutrient Film Technique (NFT)

3. **Deep Water Culture (DWC**):

The DWC technique includes swinging plants in polystyrene sheets, and their roots hanging down into the water. This technique is more appropriate for mechanization and most commonly used for large commercial aquaponics unit growing one specific crop like lettuce, basil or salad leaves (FAO, 2014). This system also called as the Floating System or Raft System, of aquaponics is one of the simplest and most effective technique of growing products (Timmons, 2010). In DWC system, plants are grown on raft boards, foam boards are commonly use, that drift on the surface of a container where fish are housed (Timmons, 2010). Plants are held in the raft boards using net pots packed with growing media, and the roots of plants hang down into the nutrient rich water (Timmons, 2010). This helps to the plants allows to absorb large amounts of nutrients and oxygen, serving in rapid growth. An air pump is essential to oxygenate the water for the fish and support breathe to the roots. Care should be taken that avoid any fish into the system that could eat roots of the plant, For example, herbivorous fish such as carp and tilapia. On the other hand, several small carnivorous species of fish like, mollies, guppies, and mosquito fish, can be used effectively to manage mosquito larvae (FAO, 2014). The polystyrene sheets must have a definite number of holes drilled to fix the net cups or sponge blocks, provide support to each plant. The quantity and the holes location is dictated according to the type of vegetable and the distance preferred between the plants, wherever smaller plants can be spaced more closely (FAO, 2014).

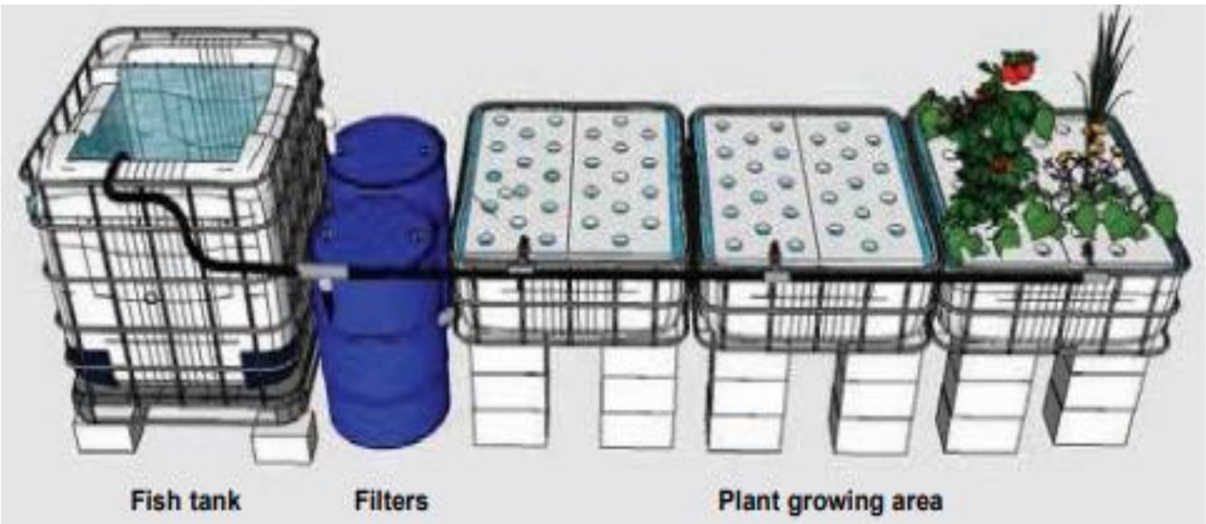

Figure 4: Deep Water Culture (DWC)

Essential components of an aquaponic unit:

All aquaponic systems required several common and necessary components. There are basic components that are essential to the functioning of any system design are as follows (FAO, 2014):

1. Fish tank:

Fish tanks are an important component in every unit. Tank shape significantly affects water circulation, and it is relatively risky to have a tank with poor circulation. Although fish tank of any shape will work however round tanks with flat bottoms are recommended. The round shape allows to circulate water uniformly and carryings solid wastes towards the centre of the tank by centripetal force. Square tanks with flat bottoms are perfectly conventional, but it wants more active solid-waste removal. If an odd-shaped tank is to be used, it can be required to add water pumps or air pumps to ensure proper circulation and remove the solids. Therefore, it is important to select a tank to fit the characteristics of the aquatic species reared because many bottom dwelling fish species show better growth and less stress with sufficient horizontal space. Plastic and fibreglass are suitable to install and are fairly light and movable. In case of using plastic containers, make assured that they are UV-resistant because direct sunlight can destroy plastic. Low-density polyethylene (LDPE) tanks are preferable to use because of their high resistance and food-grade characteristics. For aquaponics natural ponds are problematic because of natural biological processes, already taking place in the substrate and bottom mud can be stiff to operate and the nutrients are frequently previously used by aquatic plants. Cement or plastic-lined ponds are highly acceptable as a low-cost option. One of the simplest method of fish tank is a hole burrowed in the ground, enclosed with cinderblocks or bricks, and then enclosed with a waterproof liner including polyethylene plastic. Other options include second hand containers, such as intermediate bulk containers (IBCs) or barrels and bathtubs. It is very significant to assured that the vessel has not been used earlier to store toxins. Toxic material, including chemicals of solvent-borne, will have entered into the permeable plastic itself and are difficult to remove with washing.

White or other light colours are highly recommended because they permit easier viewing behaviour of the fish and the waste settled at the tank bottom. The tanks of white colour will also replicate sunlight and helps to keep water cool. All fish tanks must be covered as shade covers to avoid algal growth as well as avoid fish from jumping off (occurs in case of water quality is sub-optimal or with newly added fish), prevent entering leaves and debris, and prevent predators such as birds and cats from attacking the fish. Frequently, agricultural shading nets that block 80–90 percent of sunlight are used. The shade cloth can be attached to a simple wooden frame helps to provide weight and make the cover easy to remove.

Sump tank:

The sump tank is the lowermost point in the system, where water is collected; water constantly runs downward to the sump. This is frequently the place of the submersible pump. Sump tanks have to be smaller than the fish tanks, and must be capable to hold between the volume of ¼ and 1/3 of the fish tank. The sump required to be huge sufficient to hold at least the complete volume of water in ebb-and-flow type media beds. In media bed units mainly used external sump tanks; though, for DWC units the definite hydroponic canal have being used as a sump tank or pump house also. A Very small units, with fish tanks up to 200 litres, sump tank not a significant component, only the fish tank carry water pump to the grow beds, provides water drips back down into the fish tank. While, for larger units a sump is very useful component.

Grow media:

Volcanic gravel:

For the media bed units, volcanic gravel is the utmost commonly used medium and is suggested where available. The greatest qualities of volcanic gravel such as, it can be economical and easy to obtain, it has a very large surface area to volume ratio, and it is virtually chemically inactive. A surface area to volume ratio of volcanic gravel is about 300 m^2/m^3, dependent on the size of particle, that provides sufficient space for bacteria to colonize. Volcanic gravel is abundantly available in many places throughout the world. The suggested volcanic gravel size is 8-20 mm in diameter.

Limestone:

Limestone is the most common and cheapest form of gravel available. It is better to use where water sources are very low in acidic or alkalinity, as in cases of alkaline water it would demand for constant acid corrections of incoming waters. However, a small adding of limestone can benefit to counterpoise the acidifying effect of nitrifying bacteria, which can offset the requirement for consistent water buffering in well balanced systems. Limestone, is less necessary than other media for harvesting and planting, and if the appropriate granulometry is not selected it can chance to blockage.

Other possible media choices:

Possible to use other media for aquaponics consist of: river-bed gravel, which is usually called limestone but depending on the granulometry it can have a less surface area to volume ratio; pumice also called rockwool, a white/grey volcanic material are usually used as growing media in hydroponics; plastic floats and recycled plastic, required to hold on submerged layer of gravel on top; or organic substrates such as peat moss or rice hull, coconut fibre, sawdust, which are often cheap but risk becoming anoxic, failing over time and blockage the system.

Mechanical filter:

Mechanical filtration is the most important part of the recirculating system. Mechanical filtration is essential to the separation and carrying away of solid and suspended waste of fish from fish tanks. Therefore, it is important component to take off these wastes for the good health of the system, as anaerobic bacteria are released harmful gases if solid waste still available inside the fish tanks it will decompose. Furthermore, the wastes can choke systems and disturb water flow, producing anaerobic conditions to the plant roots. There are a few types of mechanical filters. The simple one is a screen or filter placed between the grow bed and the fish tank. This screen catches contains solid wastes, and it required cleaning regularly. Likewise, leaving water of fish tank can pass into a small container of particulate matter that separate from the media bed; this container is easy to clean periodically. These methods are effective for small-scale aquaponic units, however, inadequate in larger systems using more fish where the amount of solid waste is appropriate. There are various types of mechanical filters, such as sand or bead filters, sedimentation tanks, radial-flow clarifiers and baffle filters; individually they can be used according to the number of solid wastes that required to be removed.

Biofiltration:

Maximum fish waste is not filtering by a mechanical filter as these wastes are dissolved directly in the water, and these particles size is very small to be mechanically removed. Therefore, biofiltration is very important process of conversion of ammonia and nitrite into nitrate by microscopic bacteria. Biofiltration is essential in aquaponic system because ammonia and nitrite are lethal even at little concentrations, however plants require the nitrates to grow. In an aquaponic unit, a biofilter provide the fluctuation of water will breakdown very fine objects not captured by the clarifier, which further avoids waste build up on roots of plants in NFT and DWC system. The biofilter is designed such a way that a huge surface area provided with oxygenated water. The biofilter is fitted between the hydroponic containers and the mechanical filter. The minimum volume of biofilter container have to be 1/6 that of the fish tank. One usually used biofilter medium is Bioballs, a perfect biofilter material, as they are small in size, plastic items specifically shaped that have a very huge surface area for their volume (500–700 m^2/m^3). Other media can be used, such as nylon shower poufs, plastic bottle caps, netting, polyvinyl chloride (PVC) shavings, nylon scrub pads and volcanic gravel. Any biofilter essential a high ratio of surface area to volume, be inert and be easy to rinse.

Aeration:

Aeration is another required component for aquaponic systems. An easy way to make use of an air pump, air pumps insert air into the water through air pipes and air stones lie inside the fish tank. This makes sure that the levels of DO in the water are continuously increasing. Additional DO is a vigorous factor of NFT and DWC units. Air stones are situated at the end of the air line, it helps to diffuse the air into smaller bubbles. Small bubbles have greater surface area than large bubbles because small bubbles allow oxygen into water better than large bubbles; thus, these kinds of the aeration system more effective and helpful to saving on costs. Biofouling will occur therefore air stones must be regularly cleaned first with a chlorine solution to kill deposit bacteria and then, if needed, use a very mild acid to reduce mineralization, or when the inconsistent flow of bubbles can be replaced it.

Water pump:

Usually, an impeller-type submergible water pump is recommended also is it practised as the heart of an aquaponics unit. External pumps can be used, but they have need of extra plumbing and are more suitable for larger designs. High-quality water pumps should be used preferably as guarantee of a elongated life span and energy efficiency. High-quality pumps will sustain their pumping capacity and effectiveness for least 1–2 years, with provide 3-5 years of life span, however low-grade products will have shorter life leading to considerably reduced water flows. Use the minimum number of connections between the pump and the fish tanks. It is important that periodic cleaning is necessary therefore, fit the submersible pump in an accessible location while installing an aquaponic unit. Certainly, the internal filter will be required to clean every 2–3 weeks. Submersible water pumps never run dry whether they are run without water will break.

Plumbing materials:

Every system has need of a choice of PVC pipe, connections and fittings of PVC pipes, tubes and hoses. These helps to flow water into each component through the channels. Uniseals, bulkhead valves, Teflon tape and silicone sealant are also required. The components of PVC are join together by using PVC cement in a permanent way, whether the plumbing is not permanent than silicone sealant can be provisionally used and the joints are not under high water pressure. In addition, some general implements such as hand saws, electric saws, hammers, drills, screwdrivers, levels, measuring tapes, channel-locking pliers, pliers, etc are required. One special tool is essential for injecting the pipes into the fish tanks and filters is a hole-saw or spade bit, that is used in an electric drill to construct holes up to 8 cm, furthermore for constructing holes in the PVC or polystyrene grow beds in NFT and DWC systems. While using plumbing material in the system it should be never earlier been used to hold lethal substances. It is also important that the plumbing material have to food-grade quality to avoid possible leeching of chemicals into the water system. It is also important to usage of black colour pipes and non-transparent to light, which will stop algae growing.

Water testing kits:

Simple water tests are a requisite for every aquaponic unit. Colour-coded freshwater test kits are easily available, simple to use and, a reasonably priced thus these are recommended. These kits are useful to test pH, ammonia, nitrate, nitrite, GH (General hardness) and KH (Carbonate hardness). While using kits be sure that the manufacturers are consistent and valid the expiration date. Other methods can be used contain test strips or digital meters. A thermometer is essential to measure water temperature. Furthermore, if there is possibility of saltwater in the source water, fairly economical hydrometer, or a more accurate but more expensive refractometer can be used.

Plants in Aquaponics:

Almost any type of plant including vegetable, fruit, herb, and even flowering plants can be grown in an aquaponic system. The selection of plants will depend on what type of system you are used to grow, as root systems essential to be well-suited with the system design. For example, plants like little or no root vegetables will grow well in a DWC system, however plants with root structure will thrive best in grow beds (Bernstein, 2014). The list of plants can be grown in an aquaponic system are given below.

Vegetables:	**Fruits:**	**Flowers:**	**Herbs:**
• Lettuce • Spinach • Beans • Peas • Cucumbers • Peppers • Squash • Broccoli • Tomatoes	• Watermelon • Strawberries • Banana	• Rose • Marigold • Sunflower	• Basil • Lemongrass • Wheatgrass • Oregano • Thyme • Sage • Cilantro • Parsley

Fish in aquaponics:

The fish select to grow will have an effect on the size of aquaponic system, specific temperature and water quality requirements. Some fish species have recorded tremendous growth rates in aquaponic units. Fish species suitable for farming in aquaponic system include (Bernstein, 2014) and (FAO, 2014):

1. **Tilapia:** Tilapia is the most popular fish to grow commercially and personally in an aquaponic system. They are very easy to grow, do best in warm temperatures, and are relatively durable when it comes to changing water quality levels that are common in the setup of initial system. Tilapias temporarily tolerate water temperatures extremes of 14 and 36 °C, they do not feed or grow below 17 °C, and they die below 12 °C. To ensure good growth rates, the ideal range is 27–30 °C. They are resilient to many parasites, pathogens and handling stress. A benefit to growing tilapia is that they can grow from fingerling size (50 g) to maturity (500 g) in about 6 months which is relatively quick. Tilapias are omnivores feeder, they eat meaning both plant- and animal-based feed. Tilapias also the candidates for many alternative feeds. But care should be taken that tilapias eat other fish, particularly their own young; the tilapia should be separated by size in breeding time. Tilapias can be aggressive, particularly in low densities, because males are territorial. Thus, the fish should be kept at high densities in the grow-out tanks.

2. **Catfish:** Catfish is grow very quickly and can be easily stocked at very high densities, up to 150 kg/m^3. They are ideal for aquaculture and aquaponics because these species are air breathers, tolerate high to low DO levels and high ammonia levels also having resistant to many diseases and parasites. For beginners or for aquaponists, catfish are the easiest species to grow also beneficial in areas where the supply of electricity is not reliable. Like tilapia, catfish can grow best in warm water and have a preference a temperature of 26 °C. Catfish are benthic fish, therefore they occupy only the bottom portion of the tank. If tanks are overcrowded, catfish can hurt each other with their spines. When farming catfish, we can use a tank with greater horizontal space than vertical space, thus permitting the fish to spread out along the bottom. Otherwise, many farmers farming catfish with another fish species that utilize the upper portion of the tank, such as tilapia, bluegill sunfish or perch.
3. **Carps:** Like tilapia and catfish, carps are tolerant to relatively low DO levels and poor water quality, but they take a considerably larger tolerance range for water temperature. Carp can survive at temperatures as high as 34 °C and low as 4 °C therefore these species are an ideal selection for aquaponics in both temperate and tropical regions. Best growth rates are obtained of these species are in between 25 °C and 30 °C. The supply of roots, between other crop residues, would be also very helpful to the nutrient pool in the aquaponic system, as their digestion through the fish and the sequential waste mineralization would return most of the miconutrients back to the plants.
4. **Ornamental fishes:** Koi carps and other ornamental fishes are best option for vegetarian aquaponic cultivators. Koi carps or Gold fish are very easy to grow, widely available, also have a high resistance to a variety of water conditions and thus are good candidates for an aquaponic system. Koi is a hardy fish but need a minute more attention and consideration than a goldfish. Once they reach maturity, can be sold for very high prices, which makes them an attractive fish to grow (Bernstein, 2014). Other species that have been shown to thrive well within an aquaponics system are pacu, guppies, tetras and mollies.
5. **Other options of fish to consider are:** Catla (*Catla catla*), Rohu (*Labeo rohita*), Channel Catfish (*Ictalurus punctatus*), Perch (*Anabas testudineus*), Trout (*Oncorhynchus mykiss*), Freshwater Prawn (*Macrobrachium rosenbergii*) etc.

Fish health management (FAO, 2014):

- **Fish feed:** One of the most important parts for any aquaponic system is fish feed. It can be purchased or self-made. The use of quality manufactured fish feed pellets strongly recommends because they are a whole food for fish, as the pellets fulfill all the nutritional needs of the fish. There are different sizes of feed pellets, ranging from 2 to 10 mm. The recommended size of these pellets depends on the size of the fish. Fry and fingerlings have small mouths and cannot consume large size pellets, whereas if the pellets size are too small, large fish waste their energy. If possible, the feed must be buying according to every stage of the lifecycle of the fish. Otherwise, large size pellets can be crushed with a grout and crusher to make powder for fry and crumbles for fingerlings. A useful technique of feeding is to permit fish to feed for 30 minutes, 2–3 times for every day, and then take out all remaining food. Avoid overfeeding as a result in an increase of waste in the fish tanks and canals, leading to toxic zones, diseases, fish and plant stress, and poor growing conditions.

Feed rate ratio for aquaponics

- 40–50 gm of daily feed/ m^2 (leafy greens).
- 50–80 gm of daily feed/ m^2 (fruiting vegetables).
- Fish feeding rate: 1–2 %/day of their body weight.
- Fish stocking density: 10–20 kg/1000 litres.

- **Stocking density:** The fish releases carbon dioxide (CO2) by way of respiration, or breathing into the water. This carbon dioxide lowers pH for the reason that CO2 transforms naturally into carbonic acid (H2CO3) upon contact with water. If the fish stocking density of the unit is higher, then more carbon dioxide will be released, therefore lowering the overall pH level. The fish stocking density depends on types of systems. The recommended maximum stocking density for 1000 litres of water is 20 kg of fish. Higher stocking densities need extra advance aeration techniques to maintain the DO levels steady for fish, along with an extra multifaceted filtration system to deal with the solid waste. For aquaponics beginners are strongly suggested not to surpass the stocking density of 20 kg per 1000 litres. This is mainly the case where a continuous electricity supply is not assured, as a transitory discontinuity can destroy all of the fish within an hour at higher stocking densities. This same stocking density can applies for any size tank larger than 500 litres; If using smaller tank than 500 litres, reduce stocking density to one-half, or 1 kg/100 litres, however it is not suggested to grow fish for feeding in a tank smaller than 500 litres. For example, an average tilapia weighs 500 g at harvest size and 50 g at stocking size.
- **Fish disease:** Disease occurred in the case of an inequity between the fish, causative agent/ the pathogen and the environment. The animal weakness and a higher occurrence of the pathogen in certain conditions cause disease. An aquaponic system is a lesser amount of susceptible to pathogen introductions and disease eruptions because of enhanced control of inputs and in the management of crucial water and environmental parameters. In the case of entering water from water bodies, the adoption of simple slow sand filtration can protect the aquaponic system from bacterial introduction or any possible parasite. Likewise, the removal of snails and small crustaceans, also avoiding the entrance or the contagion from birds and animals, will be helpful to counterbalance the problems of parasites as well as possible bacterial contagion. Prevention is the best way to avoid disease in fish. It is significant to observation of fish daily and monitoring for disease, if present, to be treated as much as possible to prevent more fish from being infected. The following are the lists of common physical and behavioural symptoms of diseases.

External signs of disease:

- Exposed fin rays, ragged fins

- Ulcers on body surface, white or black spots, discoloured patches
- Abnormal body configuration, twisted spine, deformed jaws
- Prolonged abdomen, swollen appearance
- Gill and fin necrosis and decay
- Cotton like lesions on the body
- Swollen, popped out eyes (exophthalmia)

Behavioural signs of disease:

- Lethargy, different swimming patterns
- Changes in feeding habits, poor appetite
- Fish breathless at the surface
- Fish rubbing or scraping against objects
- Difficulty maintaining buoyancy, odd position in water, head or tail down

Water quality in aquaponics (APHA, 2005):

Water is the medium through which the fish receive their oxygen and plants receive their nutrients. It is very essential to know the basic water chemistry and water quality and in order to properly manage aquaponics. Water testing is essential to keeping good water quality in the system. Test and record the following water quality parameters each week: water temperature, pH, nitrate and carbonate hardness. At system start-up, ammonia and nitrite tests should be used and if abnormal fish mortality raises toxicity concerns. The ranges for each water parameter are as follows:

Water parameter	Optimum range
pH	6-7
DO	5–8 mg/litre
water temperature	18-30°C
Ammonia and	0 mg/ litre
nitrite	0 mg/ litre
nitrate	5-150 mg/ litre
Light	Indirect natural light

Advantages of aquaponic food production (FAO, 2014):

- Sustainable and intensive food production system.
- Tremendously water efficient.
- Does not require soil.
- Two agricultural products i.e. fish and vegetables are produced from one nitrogen source.
- Can be used on non-arable land such as deserts, degraded soil or salty, sandy islands.
- Does not use chemical pesticides or fertilizers.
- Qualitative production and higher yields.
- Higher level of biosecurity and lower risks from outer contaminants.
- Organic like production and management.
- Creates little waste.
- Information base and construction materials are widely available.

Disadvantages of aquaponic food production (FAO, 2014):

- Initial start-up costs are expensive compared with hydroponics or soil vegetable production.
- Knowledge of plant, bacteria and production of fish is necessary for each farmer to be successful.
- Requirements of plant and fish do not always match perfectly.
- Energy demanding.
- Daily management is compulsory.
- Requires consistent access to electricity, plant seeds and fish seed.

The main variables to consider when balancing a unit (FAO, 2014):

- At what capacity will the system function.
- Method of aquaponic production.
- Type of fish (carnivorous vs. omnivorous, activity level).
- Type of fish feed (protein level).
- Type of plants (fruits, leafy greens or tubers).
- Type of plant production (single or multiple species).
- Environmental conditions and water quality.
- Method of filtration.

Conclusion:

Aquaponics is basically a recirculation culture system involves culture of horticulture plants along with fishes. The fish excreta help to provide nutrients for the plants, while the plants clean the water, generating an appropriate environment for the fish growth. Various plants are suitable for this system; however which ones work for a particular system depends on stocking density and the maturity of the fish. Aquaponic system provides the benefit of using lesser land area, less water, less labour and waste renewal.

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GENETIC MODIFICATION AND NANOBIOTECHNOLOGY: REDEFINING CROP TRAITS FOR SUSTAINABILITY

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Abstract:

The agroecosystem faces enormous challenges because ofrapid population growth, increasing global food demand, excessive water use, high energy consumption, substantial food wastage, inefficient agrochemical use, environmental degradation, and climate change. To address these pressing issues and support sustainable agricultural practices, genetic modification, and nanobiotechnologyare emerging fieldsfor improving crop productivity in the modern era. This chapter delves into the integration of these technologies to enhance crop traits for sustainability. Biotechnology is a powerful tool for boosting agricultural productivity. It allows for genetic modifications in crops to improve their ability to withstand harsh conditions, which is difficult to achieve through conventional breeding methods. Advances in biotechnological techniques such as genetic engineering, genome editing, RNAmediated gene silencing, coupled with next-generation sequencing and genome mapping, allow for precise and efficient genetic modifications in plants. Concurrently, nanotechnology employs nanomaterials as carriers, utilized in nanofertilizers, nanopesticides, nanosensors, and other applications in plant growth and crop production. These innovations mark a paradigm shift towards sustainable agriculture, with nanotechnology and genetic modification playing crucial roles in optimizing resource use, reducing environmental impact, and ensuring food security amidst climate change.

Keywords: Sustainable Agriculture, Genetic Modifications, Nanotechnology, Nanoparticles, Nanofertilizers, Nanopesticides, Nanosenors

Introduction:

Agriculture has a significant contribution to driving economic development and ensuring food security, particularly in regions vulnerable to climate variability. As the global population is predicted to exceed nine billion by 2050, we need more improved agriculture practices to enhanceagricultural production to ensure food availability for everyone (Schroder *et al.*, 2019). However traditional organic farming techniques and costly cellular agriculturebased foods lack the scalabilityto meet the increasing food demands for such a large population. Therefore, managing sustainable farming practices on ever-shrinking agricultural land and decreasing water resources in the face of a growing human population presents one of the most significant environmental and food security challenges of the 21st century.

Sustainable crop production involves cultivating crops in a manner that minimizes harm to the environment, preserves biodiversity and maintains the quality of the harvest. Sustainable agriculture involves optimizing soil nutrient and water resource utilization, effective agro-waste management, reducing fertilizer dependency, controlling plant diseases, and implementing advanced farming practices (Khan *et al.*, 2022). However, it faces numerous challenges because of the climate shifts during the past few decades, such as drought, climate change, soil degradation, and water pollution. Drought is a serious problem that shows up as a shortage of water and is getting worse in terms of intensity, duration, and frequency. Due to its effects on biotic and physicochemical characteristics, this stress may hinder the growth of plants (Zaib *et al.*, 2023). Extreme weather events globally have reduced crop yields and present serious concerns for agriculture and food security Variations in climatic conditions also have a notable impact on pests, diseases, weeds, and insects, influencing their abundance, distribution, and ability to survive winters (Alotaibi, 2023). The overuse of chemical pesticides and fertilizers, overgrazing, and other practices are some of the reasons that cause soil degradation in agriculture. Reduced soil fertility and biodiversity can result from chemical fertilizers' ability to change the pH of the soil, deplete vital nutrients, and disturb microbial ecosystems (Adedibu., 2023). Water contamination is an additional urgent ecological issue linkedto farming. Water can get contaminated by agricultural operations, such as using chemical pesticides and fertilizers, managing manure and trash, and installing irrigation systems. (Steinwand & Ronald., 2020).

To achieve sustainability, crop production needs to shift from traditional methods to modern technologies. Genetic modification and nanobiotechnology hold the potential to revolutionize agriculture by improving crop traits for greater sustainability and could contribute to enhancing productivity, utilizing resources efficiently, boosting farmer’s economies, and supporting an eco-friendly, pollution-free environment. These innovative techniques open up new opportunities to enhance crop productivity, and nutritional valuebesides utilizing resources efficiently boosting farmer’s economies, and supporting an eco-friendly, reducing environmental impacts (Munaweera *et al.*, 2022). Comparing genetic modification and nanobiotechnology to traditional crop breeding methods unveils their distinctive strengths and capabilities. Conventional breeding relies on natural genetic variation and selection process, while genetic modification enables precise gene editing and targeted trait manipulation. Genetic modification involves altering the genetic makeup of organisms to incorporate favourable traits, such as resistance to pests, tolerance to drought, or increased nutrient levels (Kumar *et al.*, 2020). Therefore, by genetically engineering crops to express specific traits, scientists can develop varieties that are better adapted to changing environmental conditions. On the other hand, nanobiotechnology utilizes nanoscale materials and tools to intricately manipulate biological systems at the molecular level, enabling precise control over plant functions and interactions. Nanotechnology presents significant potential for advancing sustainable agriculture by improving the efficiency of agricultural inputs, leading to increased production and improved crop yields (Joshi *et al.*, 2019). Certain emerging domains of nanotechnology offer significant potential for resolving various foodrelated problems. These includes improving nutrient delivery, enhancing protein bioseparation, enabling rapid sampling of biological and chemical contaminants, facilitating solubilization, and nano-encapsulating nutraceuticals (Elizabath *et al.*, 2019). These approaches promote environmental sustainability, preserve ecological balance, and ensure economic stability. Hence, leveraging these technologies, can speed up crop improvement and develop crops with traits customized for specific environments and needs.

Role of biotechnology in crop production

Biotechnology enhances crop production by overcoming challenges that conventional breeding methods face in improving stress tolerance. Techniques like genome editing, genetic engineering, and RNA-mediated gene silencing, supported by advanced sequencing and genome mapping, enable precise and rapid genetic modifications in plants. These advancements help in developing new crop varieties that meet food demands and adapt to climate change. Crop genetic engineering stands out as a promising solution to contemporary agricultural challenges. Genetic engineering provides details of superior alleles and haplotypes that could be beneficial inenhancing crop production. Worldwide, there are over 17,000 institutes dedicated to conserving and sustainably utilizing plant genetic resources, housing more than 80,000 plant species preserved in approximately 3,400 gardens. These resources include more than 5.4 million accessions from over 7,051 genera, which are currently stored in approximately 711 gene banks, 16 regional centres, and across 90 nations. These collections aim to conserve crop species, their wild relatives, cultivars, and breeding materials. Conventional breeding is a time-consuming process hindered by various factors such as high heterozygosity, auto-incompatibility, extended life cycles, labour requirements, and prolonged juvenile periods. As a result, biotechnological innovations, offer more robust and efficient means for the genetic improvement of crop (Das *et al.*, 2023).

Genetically modified crops: Role and impact

Genetically modified (GM) crops are crop plants whose genetic makeup has been altered through genetic engineering methods. Genetic modifications improve the existing traits or introduce new traits that are not naturally found in the crop species. These modifications are achieved by inserting specific segments of foreign nucleic acid or gene sequences into their genomes through techniques like *Agrobacterium*-mediated transformation or direct gene transfer. The Ti plasmid became a key vector for introducing foreign genes into plant cells after the discovery of *Agrobacterium tumefaciens* naturally integrating Ti plasmid DNA into host plant genomes in 1977. This discovery coincided with the development of the first transgenic plants that year: antibioticresistant petunias and tobacco. In 1994, the transgenic tomato 'Flavr Savr', developed by Calgene (Monsanto), which had a longer shelf life or delayed ripening, was approved by the Food and Drug Administration (FDA) for sale in the USA. Subsequently, various other transgenic crops including canola with modified oil composition, Bt potato, Bt maize, Bt cotton, bromoxynil herbicide-resistant cotton, and glyphosate-resistant soybeans, received approval for commercialization. In a significant breakthrough, research has proved that expressed the "phaseolin" gene from beans in sunflowers, demonstrating that a plant gene could still be functional even after transfer to a taxonomically distinct family of flowering plants.

Transgenic crops have been developed and authorized for commercialization primarily for the following features: herbicide tolerance, insect resistance, disease resistance, tolerance to abiotic stresses, and nutritional enhancement.Glyphosate-resistant transgenic crops have been developed by expressing a glyphosate-insensitive form of *epsps* obtained from *A. tumefaciens* strain CP4, mutant versions of maize *epsps*, or a chemically synthesized gene similar to the *grg23* gene from *Arthrobacterglobiformis*. In 1996, glyphosate tolerant "Roundup Ready" soybeans, containing the cp4epsps gene, became the first herbicidetolerant transgenic crop commercially available. The *cry* genes, originating from soil bacteria *Bacillus thuringiensis*, are widely utilized in developing insect-resistant transgenic crops. *Cry* genes from different isolates of *Bacillus thuringiensis*, provide resistance against a diverse range of insect pests, including Lepidopterans, Coleopterans, and Dipterans. Cotton was the first commercially successful crop in which *cry* genes were incorporated to provide resistance against lepidopteran insect pests (Kumar *et al.*, 2020).

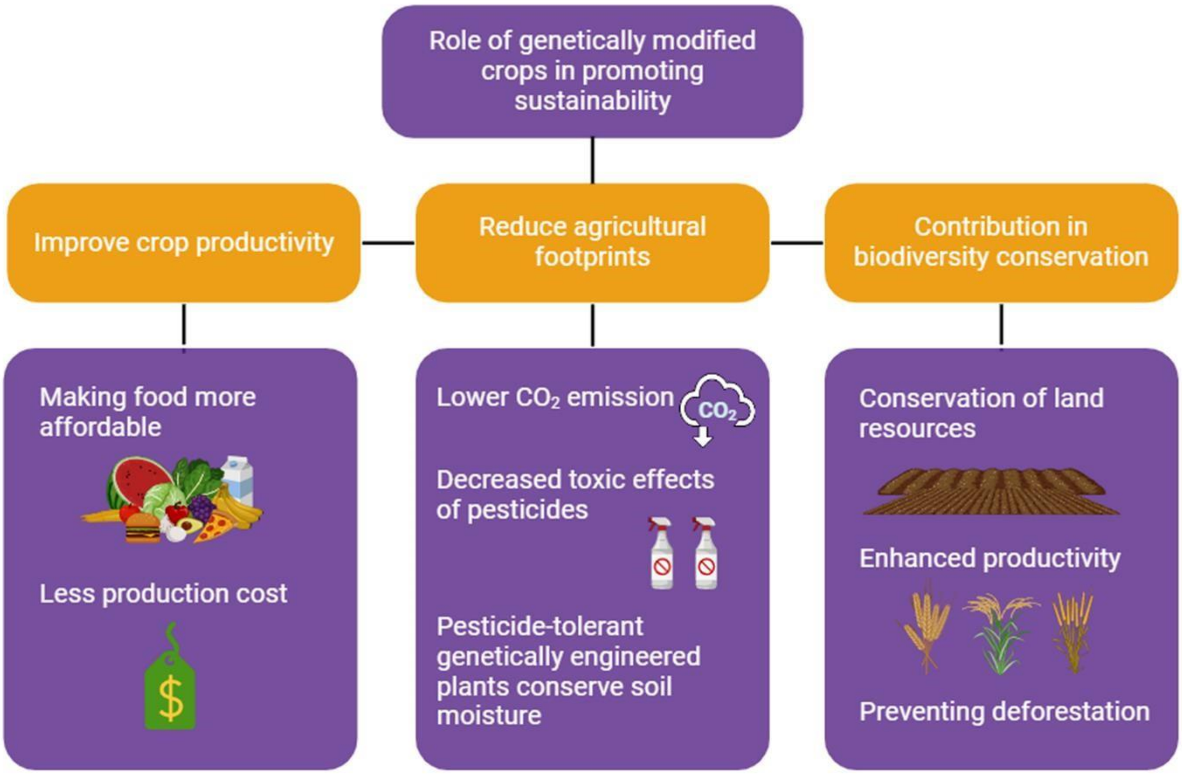

Figure 1: Importance of genetically modified crops for enhancing sustainability

Some transgenic approaches have focused on modifying the amino acid composition of plant proteins to enhance nutritional value by engineering essential amino acid metabolic pathways. For example, transgenic wheat and rice have been developed by expressing lysinerich pea legumin protein in their endosperm. Another notable achievement was the introduction of a seed storage protein from *Amaranthus hypochondriacus* into cereals, which is rich in all essential amino acids required by humans (Kumar *et al.*, 2020). Oils low in saturated fats and high in polyunsaturated fatty acids (PUFAs) are considered healthier for human consumption. Omega-3 fatty acids are known for their beneficial role in brain development and reducing the risk of cardiovascular disease. Recently, *Camelina sativa* has been genetically modified with genes from marine microorganisms, enabling it to generate significant amounts of omega-3 long-chain PUFAs like docosahexaenoic acid and eicosapentaenoic acid, which are like those found in fish oil (Usher *et al.,* 2017).

Genome editing: The emergence of genome editing technology in recent years has transformed the modification of crop genomes, offering unparalleled ease, precision, and accuracy. This set of innovative techniques, utilizing various site-specific nucleases like Zinc Finger Nucleases (ZFNs), Transcription Activator-Like Effector Nucleases (TALENs), and the CRISPR/Cas system, has effectively mitigated concerns about the unpredictability and inefficiency linked to conventional random mutagenesis and transgenesis methods (Kumar *et al.,* 2020).

RNA-mediated gene silencing: Through overexpression of RNA sequences, RNAi technology can inhibit the expression of specific genes or control gene expression prior to translation. This technology encompasses three primary methods in plants: miRNA silencing, transcriptional gene silencing, and post-translational gene silencing (Borges and Martienssen 2015). Most virus-resistant transgenic crops have been developed using gene silencing techniques like co-suppression/RNAi and antisense RNA, which target viral genes. For example, in squash, resistance was successfully achieved against cucumber mosaic virus, zucchini yellow mosaic virus, and watermelon mosaic poty virus 2by introducing the viral coat protein (cp) gene as a transgene.

Next-Generation Sequencing (NGS): Harnessing the genetic diversity of crops and their wild relatives enables their improvement by combining genes to create plants with enhanced performance in agriculture and food industries. Next-generation sequencing (NGS) technology analyzes whole genomes, revealing the genetic basis of important phenotypic differences and identifying novel variations. Genome sequencing, assembly, and annotation have been completed for several key crops, such as rice, soybean, chickpea (*Cicer arietinum*), pigeon pea (*Cajanus cajan*), foxtail millet, and pearl millet (*Pennisetum glaucum*), elucidating genotype-phenotype relationships (Varshney *et al.,* 2019). Wheat, one of the most widely cultivated crops globally, is severely affected by *Puccinia striiformis*. Sequencing techniques have successfully identified effector proteins that could aid in breeding wheat varieties resistant to pathogens. Additionally, NGS has uncovered drought-tolerant genes in *Populus* sp. (poplar) and *Trifolium pratense* (red clover).

Climate ready crops: Among the top 15 crops that provide 90% of the world’s food energy intake, rice, maize, wheat, and soybean dominate the global food system. Significant efforts have been made to enhance major cereal and non-cereal crops using advanced biotechnological approaches to make them resilient to climate challenges (Munaweera *et al.,* 2022). Thus, innovative applications of biotechnology are opening new avenues for food and energy production, particularly in nations where food manufacturing is still scarce. As food security demands grow in the future, biotechnology will become increasingly advantageous in the agricultural sector.

Nanotechnology: A powerful tool for crop transformation

Nanotechnology encompasses the design, characterization, production, and application of structures and systems at the nanoscale, manipulating shape and size to advance various fields, including agriculture. With the advancement of scientific knowledge, nanotechnology provides crucial insights into crop biology, enabling targeted breeding to improve yield and nutritional value. It facilitates genetic reform in plants and acts as a defensive shield against pathogens, fostering crop improvement and enabling efficient disease management (Elizabath *et al.*, 2019). Advances in nanotechnology, coupled with gene sequencing, enable precise identification and utilization of plant genetic resources to develop stress-resistant crops.

Applications of nanotechnology in sustainable agriculture

The integration of nanotechnology in agronomy, particularly in plant sciences, offers a profound opportunity to transform the agricultural sector. The primary goal of nano-based agriculture is to enhance crop productivity by bolstering resilience to diverse environmental challenges such as climate variability, saline water, water scarcity and fluctuating CO_2 levels.Nanodevices serve not only as a potent tool but also play a significant role in monitoring plant growth and productivity, assessing soil composition and enabling targeted genetic modifications to improve plant functions, ultimately contributing to fostering a sustainable environment.Nanotechnology enhances crop production through several categories: nanopesticides, nanofertilizers, nanosensors, and nanobionics and by genome editing.

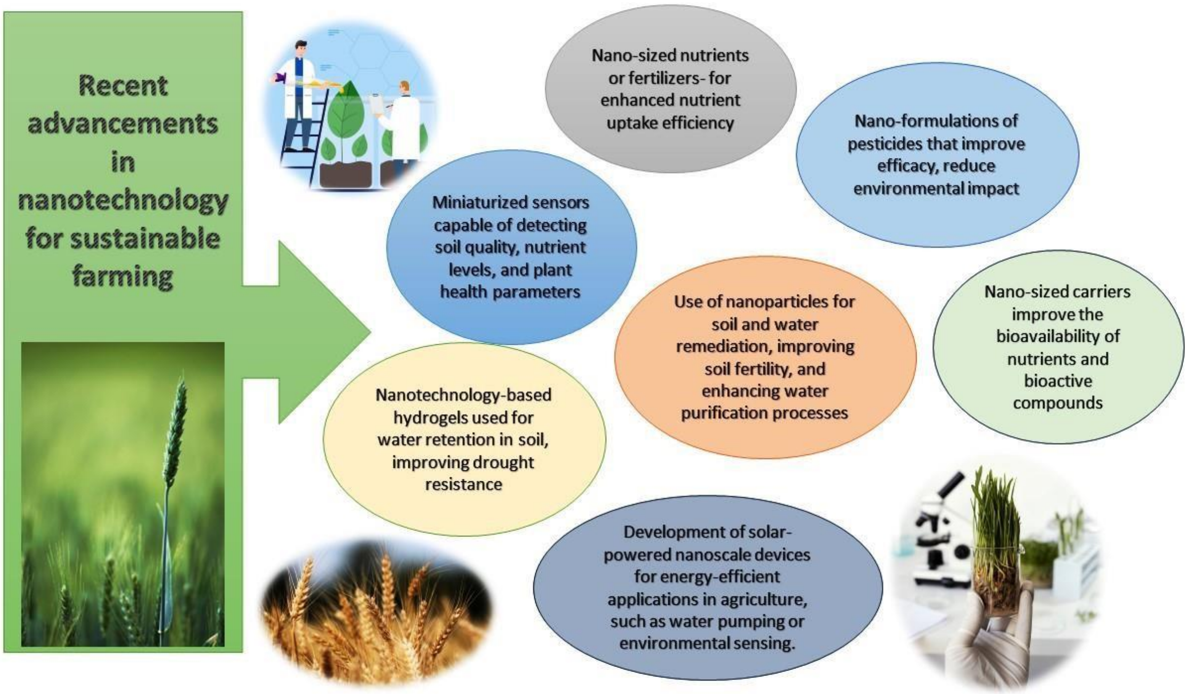

Figure 2: Figure depicting the current advancement of nanotechnology-based sustainable farming

Nanopesticides: Pesticides enhance food production by protecting crops from pests and diseases. However, conventional pesticides often result in issues like drift, poor targeting, and unintended accumulation, thereby, causing genetic mutations in pests, and environmental damage. Nanopesticides, with their precise delivery and extended lifespan, offer a sustainable solution by minimizing the use of conventional pesticides and reducing associated environmental risks. Concerning this, Pereira *et al.*, (2014) synthesized poly (epsiloncaprolactone) nanoparticles for encapsulating atrazine and evaluated their herbicidal and genotoxic effects. The nanoherbicide effectively controlled targeted *Brassica* sp. and showed reduced atrazine mobility in soil.In addition, *Allium cepa* chromosome aberration assay demonstrated reduced genotoxicity for the herbicide.Similarly, atrazine-loaded nanocapsules showed greater effectiveness against hairy beggarticks (*Bidens Pilosa* L.) and slender amaranth (*Amaranthus viridis* L.) compared to commercial atrazine products (Sousa *et al.*, 2018).In another study, nanosized absorbents derived from rice husk waste were used as carriers for the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D), resulting in significant enhancement of 2,4-D sorption and activity (Chidambaram 2016). Thefoliar application of metsulfuron methyl-loaded polysaccharide nanoparticles to weeds growing in wheat substantially reduced weed biomass compared to normal herbicide (Kumar *et al.*, 2017). This approach effectively maintained herbicidal activity at lower concentrations and significantly enhance the herbicidal efficacy. Similarly, the evaluation of nanoformulated commercial fungicide (Tebuconazole 50% + Trifloxystrobin25%) assessment at concentrations ranging from 5 to 25 ppm exhibited superior efficacy against the soil-borne fungal pathogen *Macrophomina phaseolina*compared to commercial fungicide formulation (Kumar *et al.*, 2016). The Eichhornia-mediated copper oxide nanoparticles were proved to be good antifungal agents against the fungal pathogen of the plant (*Fusarium culmorum* and *Aspergillus niger*) (Vanathi *et al.*, 2016). When compared to free-leaf extracts, nanobactericides consisting of silver nanoparticles and holy basil leaf extract exhibited increased inhibition of *Xanthomonas axonopodis* pv. *punicae* on pomegranate (Sherkhane *et al.*, 2018). Studies investigating bacterial activity revealed that copper nanoparticles inhibited the growth of bacteria such as *Agrobacterium tumefaciens*, *Erwinia amylovora*, *Dickeyadadantii*, *Pectobacterium carotovorum* and *Pseudomonas savastanoi* pv. *Savastanoi* (Varympopi *et al.*, 2020). Hashem *et al.* (2018) reported the increased efficacy and stability of anise (*Pimpinella anisum*) essential oil against red flour beetle (*Tribolium castaneum*) and suggested that nanoemulsions can help in reducing the dependence on harmful synthetic insecticides for pest control.

Nanofertilizers

Nanofertilizers boost crop yield and quality by improving nutrient use efficiency, reducing costs, and enabling smart agrochemical delivery thus, promoting sustainable agriculture. Conventional nitrogen fertilizers typically exhibit a 30-60% efficiency rate while phosphatic fertilizers can lose upto 90% due to chemical binding in soil, rendering them inaccessible to plants. However, nanocomposites containing urea and hydroxyapatite provide controlled nitrogen release and sustained phosphorous availability for four weeks (Giroto *et al.*, 2017). Fe-based nanoparticles increased the levels of vitamin C (37–67%) and amino acids in cherry radish treated plants compared to the control group (Shakoor *et al.*, 2022). Similarly, Zhou *et al.,* (2023) discovered that nano zero-valent iron enhanced rice growth rate by 13–42% and improved shoot nutrient concentration (Cu, Zn, and Fe), while increasing Fe plaque to block Cd uptake by 267%. Fe2O3 nanofibers combined with Cornelian cherry fruit extract led to increased stimulation of root and shoot biomass in barley (Rostamizadeh *et al.*, 2020). The foliar application of ZnO-NPs to *Lisianthus* leaves enhanced petal anthocyanin levels, leaf chlorophyll content, and flower numbers (Seydmohammadi *et al.*, 2020). In wheat crops, Dimpka *et al.*, (2018) found that foliar treatment of Mn-NFs enhanced Mn translocation efficiency by 22%. Similarly, Nagdalian *et al.,* (2023) investigated the impact of selenium nanoparticles (SeNPs) on barley seeds, and found that a concentration of 5 mg L^{-1} of SeNPs resulted in optimal root and shoot length, while 10 mg L−1 was best for root thickness. Recent research has shown that loading N, P, and K into chitosan nanoparticles boosts N, P, and K acquisition by 17.04%, 16.31%, and 67.50%, respectively, compared to untreated control in cultivated coffee plants (Ha *et al.*, 2018). Additionally, magnesium oxide (MgO) nanoparticles sprayed on cotton substantially increased seed cotton yield by 42.2% compared to the untreated control (Kanjana 2020).

Nanosensors

Nanotechnology has paved the way for the development of nanoscale biosensors that offer remarkable sensitivity and versatility. The incorporation of nanomaterials into sensors facilitates the adoption of advanced signal transduction technologies. The major applications of nano biosensors in the agriculture sector include direct or indirect detection of pesticides, food-borne pathogenic microorganisms, toxin contaminants, drug residues, and heavy metal ions, etc. This technology has also been extended to monitor plant growth, soil condition, crop stress, antibiotic resistance, nutrient content, or food quality. Nanosensors in plant disease detection target DNA, proteins, and volatile organic compounds. For instance, the SERS-recombinase polymerase amplification method demonstrates superior sensitivity and lower detection limits compared to traditional polymerase chain reaction for identifying key plant pathogens such as *Botrytis cinerea, Pseudomonas syringae,* and *Fusarium oxysporum* (Lau *et al.*, 2016). Researchers employed portable nanosensors utilizing upconversion nanoparticles and graphene oxide to hybridize extracted plant RNA with target sequences. They monitored fluorescence output to detect the presence or absence of specific mRNA sequences. This innovative sensor effectively detected early zinc deficiency in crops by identifying mRNAs encoding ZIP transporters (Giust *et al.,* 2018). Near-infrared fluorescent single-walled carbon nanotubes integrated with *Arabidopsis thaliana* leaves to optically monitor plant health in response to various stresses including UV-B radiation, high light and pathogen-related peptides (Wu *et al.*, 2020). Various types of nanosenors have been designed and applied to detect heavy metals. Among these, graphene-based optical nanosensors, as reviewed by Zhang *et al.,* (2018), exhibit superior performance in the detection of heavy metal ions. Surya *et al.,* (2020) developed a rapid in-field method for detecting and quantifying soil moisture content using an integrated capacitive sensor. Nanobiosensors are also used to detect nitrite and urease levels in soil and water through microfluidic impedimetric and colorimetric assay. In conclusion, nanosensors enable administrators to monitor plant health at the molecular level, significantly enhancing the efficiency of plant management. However, it is essential to carefully consider the stability of these nanosensors when applying them in agricultural system.

Nanobionics

Nanobionics in agriculture involves the use of nanoparticles and their interactions with plant systems to enhance or regulate specific functions, significantly boosting crop production. This technology can function as an artificial photosynthetic system, improvingphotosynthetic capacity, electron transfer within photosystems, pigment levels, and light absorption across the UV-visible spectrum. In this context, Vatankhah *et al.*, (2023) conducted an experiment showing that foliar application of orange carbon dots enhanced the photosynthetic efficiency of Zea mays. These carbon dots were found to enhance electron transfer efficiencies in the photosystem, attributed to their high light harvesting capacity (Milenković *et al.*, 2021). In another study, tobacco leaves treated with chitosan-modified polyethyleneimine nanoparticles (gPEI-Chi) demonstrated the ability to absorb CO_2 when exposed to a CO_2-rich environment. This treatment not only enhanced photosynthetic efficiency and CO2 storage in plants but also facilitated the conversion of CO2 into bicarbonate, which interacted with the Rubisco enzyme, resulting in a 20% increase in 3-PGA production in laboratory tests (Routier *et al.*, 2023). Polyhydroxyfullerene (PHF), a water-soluble carbon nanomaterial, has been shown to reduce plant toxicity induced by heavy metals (Pradhan and Mailapalli 2017). Similarly, the application of multi-walled carbon nanotubes (MWCNT) in *Arabidopsis thaliana* enhances plant growth by reducing paraquat toxicity (Fan *et al.*, 2018). With increasing pollution in soil, water, and air, the use of nanoparticles (NPs) for remediation aims to minimize environmental damage or prevent it altogether. Adding silicon oxide (SiO2) nanoparticles (15 mg/L) to *Triticum aestivum* seeds before germination under drought stress conditions increases water uptake as well as amylase activity (Rai-Kalal *et al.*, 2021). The integration of nanobionics in crop management seeks to support sustainable development goals and foster significant agricultural advancements. However, it's crucial to evaluate and mitigate if there are any potentially harmful effects of nanomaterials before their widespread use to ensure their contribution to sustainable development without adverse consequences.

Nanobiotechnology in genome modification

Nanobiotechnology in genome modification utilizes nanoscale materials and techniques to precisely alter genetic material, facilitating efficient genetic engineering and genome editing. Nanoparticles such as nanosheets, nanocapsules, and nanofibers serve as effective nanocarriers within plant system, enablingtargeted delivery of biomolecules and drugs. This integration of nanotechnology with genome modification enhances crop breeding by enabling precise genetic transfer. For example, Mitter *et al.* (2017) explored the use of double hydroxide clay nanosheets as nano-vectors for loading dsRNAs and RNA breakdown products of various plant viruses. They found that this method effectively protected tobacco plants against the Cauliflower Mosaic

Virus. Expanding on this research, Hajiahmadi *et al.,* (2019) utilized modified mesoporous silica-coated dsDNA for effective topical delivery of the CryIAb gene. Additionally, Demirer and Landry (2017) employed single-walled nanotubes to effectively deliver small interfering RNA (siRNA) into *Nicotiana benthamiana*, preventing nuclease degradation and facilitating post-transcriptional gene silencing to regulate plant metabolic pathways.The siRNA delivery system mediated by CNTs showed high silencing efficiency in plant cells, whereas the nanoparticles-based delivery platform exhibited effective intracellular transferable capacity (Demirer *et al.,* 2020). Polyethylenimine-coated Au NPs (PEI-AuNPs) successfully delivered siRNA into intact plant cells, achieving significant reduction in target gene expression (Zhang *et al.,* 2021). Zhao *et al.,* (2017) introduced 'pollen magnetofection,' using magnetic nanoparticles to insert foreign genes into pollen tubes. These magnetofected pollen grains are then used for pollination, leading to the production of seeds with desired genetic modifications, thus, eliminating the need for tissue culture and regeneration steps which are major challenges in transgenic plant production. Chloroplast transformation, which prevents horizontal transgene transfer to wild species via pollen, has also advanced with nanobiotechnology. Recently, researchers have utilized chitosan-complexed single-walled carbon nanotubefor chloroplast-specific transformation of foreign genes in plants (Kwak *et al.,* 2019).Therefore, the above-mentioned methods have the potential to revolutionize gene delivery in plants, streamlining the translation of basic research into practical applications where successful plant transformation is often challenging.The growing field of nanobiotechnology offerspromising opportunities for optimizing plant transformation system, althoughfurther studies are needed to ensure the stability of nanobiotechnology-assisted genome modification. Continued research in this area holds immense promise for advancing agricultural biotechnology and meeting the challenges of global food security in the coming years.

Conclusion:

Feeding the future global population will impose unprecedented demands on agriculture to significantly increase food production while mitigating its negative impacts on soil, water, and climate. The excessive reliance on agrochemicals has severely degraded crop yields, causing irreparable harm to our ecosystem. Therefore, genetic improvement of plants through biotechnology to tolerate or resist abiotic and biotic stresses will be crucial for ensuring global food security, as these stresses result in substantial yield losses worldwide each year.

Nanotechnology has introduced a variety of tools to enhance agronomic traits in plants, including improving pesticide and fertilizer efficiency, enhancing stress tolerance, and developing nanosensors for smart agriculture and genetic engineering of plants. As a result, nanobiotechnology has emerged as a promising solution to this critical issue, effectively increasing crop yield and bolstering plant survival rates. Nanomaterials have been recognized as safe delivery systems with unique potential; therefore, nanofertilizers, nanosensors, and nano-pesticides hold substantial promise in agricultural applications, contributing to agricultural sustainability. However, alongside its positive aspects, nanotechnology still faces significant gaps between laboratory research and practical application in agriculture. The potential adverse effects of nanomaterials must be carefully assessed and mitigated before their widespread application for sustainable development. Overcoming these challenges could unlock a promising and beneficial future for developing nations.

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NANOTECH INNOVATION IN WATER MANAGEMENT FOR AGRICULTURE: EFFICIENCY AND CONSERVATION

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Abstract:

Nanomaterials have gained importance in many fields of science and technology due to their unique properties. Nanomaterials are used in the agrifood sector, especially for preservation and packaging, agriculture and water quality management. Future applications will increase shelf life, food quality, safety and durability. Nanosensors will be used to detect food and water contamination. Here we examine the applications and sub-disciplines of nanotechnology in agriculture. The main points are as foolows. We described the classification and synthesis of nanometrials for agriculture and water management. We then demonstrate important applications such as nanoscale carriers, xylem packaging, nanolignocelllosic materials, clay nanotubes, photocatalysis, bioremediation of resistant pesticieds, antibiotics, waste water treatment effluents, nanobarcoding technology, quantum dots, and nanobiosensors for staining bacteria. Applications for water management include nanoscale wood driven metal particles, photocatalysis, desalination, heavy metal removal, and wireless nanosensors.

Keywords: Nanotechnology, Nanomaterials, Agriculture, Water Quality Management, Environment

Introduction:

Water remains the most precious resource essential to sustain all life on earth. However, in the twenty-first century, access to reliable and affordable clean water remains a key global challenge. Currently, the supply of potable water is under stress due to the lack of availability of freshwater and poor sanitation services. According to the World Health Organization, nearly 780 million people still lack access to clean and sustainable drinking water worldwide (World Health Organization 2012).

Agricultural products influence most aspects of life, including everyday materials, such as fuels, textiles, furniture, feedstock for biobased products including food and feed. Technology advancement is needed to achieve the future global needs from agriculture. Nanoscience and nanotechnology have shown great potential in improving food safety, quality, product traceability, nutrient delivery, enhancing packaging performance, and improving agricultural and food processing. In the present review an attempt has been made to summarize the classifi cation and the synthesis method for the nanomaterials used in agricultural practices and water quality management. Also, the application of nanomaterials in the agriculture such as nanoscale carriers, fabricated xylem vessels, nanolignocellulosic materials, clay nanotubes, photo-catalysis, bioremediation of resistant pesticides, disinfectants, agricultural wastewater treatment, nanobarcode technology, quantum dots for staining bacteria, different types of nano-biosensors along with the current research trends, future directions, opportunities and research gaps in this field has been discussed in detail. The goal of this article is to provide the perspectives of researchers working with nanotechnology to address agricultural and water quality management problems.

Nanotechnology and Research Trends in Agriculture Currently, the major challenges faced by world agriculture include changing climate, urbanization, sustainable use of natural resources and environmental issues like runoff and accumulation of pesticides and fertilizers. These problems are further intensified by an alarming increase in food demand that will be needed to feed an estimated population of six to nine billion by 2050 (Chen and Yada 2011). This above-mentioned scenario of a rapidly developing and complex agricultural system exists and greater challenges will be posed to the developing countries as, in the developing countries, agriculture is the backbone of the national economy. Nanotechnology, this vast field of the twenty-first century, is making a very significan’t impact on the world’s economy, industry and people’s lives (Gruere *et al.,* 2011; Scott and Chen, 2003). Applications of nanotechnology in materials science and biomass conversion technologies applied in agriculture are the basis of providing food, feed, fibr, fire and fuels. Through advancement in nanotechnology, a number of state-of-the-art techniques are available for the improvement of precision farming practices that will allow precise control at nanometer scale as shown in figure. Nanotechnology can also be an alternative source of fertilizer. In an experiment, it was observed that SiO_2 Nanoparticles enhanced germination in tomato (*Lycopersicum esculentum*) seeds (Manzer and Mohamed, 2014).

Agricultural products affect most components of existence, which includes ordinary materials, together with fuels, textiles, furnishings, feedstock for bio-primarily based products inclusive of food and feed. technology development is needed to obtain the future international desires from agriculture. Nanoscience and nanotechnology have shown exquisite capability in improving meals safety, nice, product traceability, nutrient delivery, enhancing packaging performance, and enhancing agricultural and meals processing. within the present evaluation an attempt has been made to summarize the category and the synthesis method for the nanomaterials used in agricultural practices and water first-class management. also, the software of nanomaterials within the agriculture which include nanoscale vendors, fabricated xylem vessels, nano-lignocellulosic materials, clay nanotubes, picture-catalysis, bioremediation of resistant pesticides, disinfectants, agricultural wastewater treatment, nano barcode generation, quantum dots for staining microorganism, special styles of nano-biosensors in conjunction with the present day research tendencies, destiny instructions, possibilities and research gaps in this discipline has been dis-stubborn in detail. The goal of this text is to provide the views of researchers operating with nanotechnology to address agricultural and water best manipulatementissues.

Currently, provision of easy and considerable fresh water is one of the maximum important demanding situations confronted through the sector for human use and industrial packages which include agriculture (Vörösmarty *et al.,* 2016; Allah, 2016). in keeping with a survey, more than one billion people within the international are disadvantaged of smooth water and the state of affairs is get- ting worse. in the close to future, it has been anticipated that common water deliver in line with individual will drop by way of a component of one 0.33, for you to bring about the avoidable prema- ture death of thousands and thousands of people in the meantime non infected water is likewise now not to be had for proper agricultural practices (move *et al.,* 2019). A large amount of sparkling water is needed in agriculture, however in flip, it contributes to groundwater polllution thru the use of insecticides, fertilizers and other agricultural chemicals. To fight this trouble, novel, sustainable and price powerful technologies can be required for the remedy of this massive quantity of waste water produced. for the duration of the treatment of wastewater, important troubles like water fine and quantity, remedy and reuse, protection due to chemical and biological dangers, monitoring and sensors have to be taken into consideration (Schoumans *et al.,* 2014; Thorburn *et al.,* 2013). studies and improvement in nanotechnology has enabled us to discover novel and economically fea- sible solutions for remediation and purification of this wastewater. available water resources are on the whole contaminated with water-borne pathogenic microorganisms like cryptosporidium, coliform micro organism, virus, and many others., numerous salts and metals (Cu, Pb, As), runoff agricultural chemicals, tens of hundreds of compounds considered as prescribed drugs and private care products (p.c.), and endocrine disrupting com- kilos (EDC) and radioactive contaminants, either clearly going on or as the end result of oil and gas manufacturing as well as mining activities due to herbal leaching and anthropogenic activities (Speed *et al.,* 1987; Jasra *et al.,* 1999). Nano-scale 0- valent iron can be used for the treatment of distillery wastewater (Homhoul *et al.,* 2011). For improving water great, nanotechnology has provided novel solutions (Fig. 1).

Nano-oligodynamic metallic particles

Physico-chemical microbial disinfection systems like chlorine dioxide, ozone and ultraviolet are being usually utilized in evolved international locations, but most of the devel- oping countries are missing those systems due to the requirement of large infra- shape which make them costly. The need of the hour is to go looking and develop opportunity cost-powerful technologies. Nanotechnology based totally oligodynamic steel debris have the potential to serve this characteristic. among those nanomaterials, silver is the maximum promising one as it's far each bactericidal and viricidal because of the manufacturing of reactive oxygen species that cleaves DNA and can be utilized for a wide range of applications. different properties consist of low toxicity, ease of use, its charge potential, excessive floor-toextent ratios, crystallographic shape and adaptableness to various substrates (Nangmenyi and economic system 2009; Chen and Yada 2011; Faunce *et al.,* 2014; Jain *et al.,* 2016). recently researches have been completed to vary the size of silver and gold nanoparticles with easy methods i.e. changing the concentra- tion of reactants. The stepped forward hobby of antimicrobial and anticancerous hobby changed into determined for them (Nandita *et al.,* 2015a; Maddineni *et al.,* 2015; Shivendu *et al.,* 2016; Janardan *et al.,* 2016). It also can be referred to that, lately traits are converting closer to in silico and computational technique closer to toxicity evaluation of inor- ganic nanoparticles (Ranjan *et al.,* 2015, 2016).

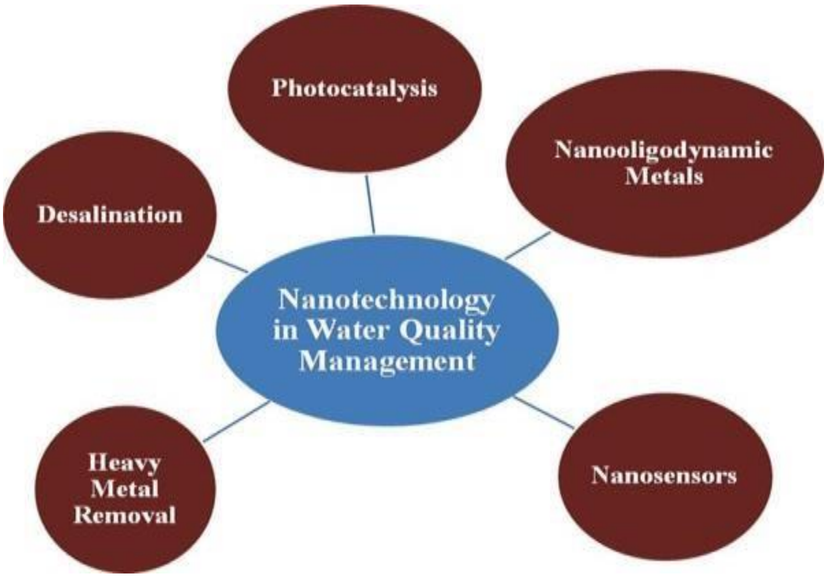

Figure 1: Diagrammatic representation of nanotechnological aspects in water quality management which includes heavy metal removal, desalination, photocatalysis, nnao-oligodynamic metals and nanosensors

Photocatalysis

Visible light photocatalysis of transition steel oxides, some other nanoscale technological development, produces nanoparticles, nanoporous fibers and nanoporous foams that may be used for microbial disinfection (Li *et al.,* 2009) and for the removal of natural contaminants like non-public care merchandise (percent) and endocrine disrupt- ing compounds (EDC). furthermore, tubular nanostructures, embedded into microbial cell wall, can disrupt its cell structure ensuing in the leakage of intracellular com- kilos, and ultimately cell death. a detailed research tendencies in the discipline of photoca- talysis has been mentioned above in element. As discussed above – the recent studies tendencies for photocatalysis using nanomaterials has been shifted from single nanoparticles to hybrid nanocomposite e.g. Ag/AgVO3 onedimensional hybrid nanoribbons with superior performance of plasmonic seen-light photocatalysis (Zhao *et al.,* 2015); fabrication of plasmonic Pt nanoparticles on Ga-doped ZnO nanopagodas array with improved photocatalytic activity (Hsien-Ming *et al.,* 2015); PbS quantum dots in ZnO@PbS/graphene oxide has been synthesized for more advantageous photocatalytic hobby (Xi-Feng *et al.,* 2015); Zirconium and silver co-doped TiO2 nanoparticles for degradation of methyl orange and methylene blue (Saraschandra *et al.,* 2015).

Desalination

Due to restricted sources of clean water, it's far possibly that in the close to future, desalina- tion of sea water turns into a main supply of fresh water. conventional desalination technology like reverse osmosis (RO) membranes are getting used but those are highly-priced because of the large quantity of electricity required. Nanotechnology has played a completely vital function in growing a number of lowenergy options, among which 3 are maximum promising. (i) proteinpolymer biomimetic membranes, (ii) aligned-carbon nanotube membranes and (iii) skinny movie nanocomposite membranes (Hoek and Ghosh, 2009; Victor *et al.,* 2014). these technologies have proven up to a thousand instances higher desalination efficiencies than RO, as those have excessive water perme- ability because of the presence of carbon nanotube membranes in their structure. a number of these membranes are worried inside the integration of other procedures like disinfec- tion, deodorizing, de-fouling and selfcleaning. In any other technique, zeolite nano- membrane may be used for seawater desalination (Liu and Chen 2013). some of these technologies can be brought in the marketplace location within the near destiny however scale-up fabrication, sensible desalination effectiveness and lengthy-time period balance are the maximum important challenges to be taken into consideration earlier than a hit commercial- ization (Yan *et al.,* 2003). Desalination using nanotechnology with the elements of carbon nanotubes (Rasel *et al.,* 2014), reverse osmosis (Peng *et al.,* 2011), forward osmosis for seawater and wastewater (Linares *et al.,* 2014) were reviewed earlier. recently many gadgets with improved efficiency and overall performance were evolved- self-sustained webs of polyvinylidene fluoride electrospun nano-fibers (Essalhi and Khayet 2014); PVA/PVDF hole fiber composite membrane changed with TiO2 nanoparticles (Xipeng *et al.,* 2014); novel incorporated machine coupled with nanofluid-based solar collector (Kabeel and Emad 2014); zinc oxide micro/ nanostructures grafted on activated carbon material electrodes (Myint *et al.,* 2014); tubular MFI zeolite membranes (Martin *et al.,* 2012); titanium oxide nanotubes/ polyethersulfone blend membrane (Abdallah *et al.,* 2014); Graphene wrapped MnO2-nanostructures (Ahmed *et al.,* 2014a); skinny film nanocomposite membranes (Arun *et al.,* 2014); Graphene/SnO2 nanocomposite (El-Deen *et al.,* 2014; Ahmed *et al.,* 2014b); carbon nanotubes (Goh *et al.,* 2013).

Removal of heavy metals

Ligand primarily based nanocoating may be utilized for effective removal of heavy metals as those have high absorption tendency. It will become fee effective as it could be regener- ated *in-situ* by means of treatment with bifunctional self-assembling ligand of the previously used nanocoating media. Farmen (2009) used crystal clean generation for water purification wherein a couple of layers of metal may be bonded to the equal substrate the usage of crystal clean technology (Farmen 2009). in keeping with, another strategy for the removal of heavy metals is the usage of dendrimer enhanced filtration and it may bind cations and anions in line with acidity (Diallo 2009). these days nanomaterials have been widely used to cast off heavy metals from water/wastewater because of their big floor area and high reactivity. metallic oxide nanoparticles, such as nano- sized ferric oxides, manganese oxides, aluminum oxides, titanium oxides, magne- sium oxides and cerium oxides, offer high floor place and unique affinity for heavy metallic adsorption from aqueous systems. so far, it has end up a hot topic to expand new technology to synthesize metal oxide nanoparticles, to evaluate their removal of heavy metals underneath varying experimental situations, to show the below- mendacity mechanism accountable for steel removal primarily based on contemporary analytical tech- niques (XAS, ATR-toes-IR, NMR, and so on.) or mathematical models, and to develop steel oxide-based totally nanomaterials of higher applicability for practical use i.e. granu- lar oxides or composite materials (Ming *et al.,* 2012). additionally, humic acid and fulvic acid exist ubiquitously in aquatic environments and have an expansion of func- tional agencies which permit them to complex with metal ions and engage with nano- substances. those interactions can't simplest regulate the environmental behaviour of nanomaterials, however additionally impact the removal and transportation of heavy metals by way of nanomaterials. as a result, the interactions and the underlying mechanisms concerned battle- rant specific investigations. Wang-Wang *et al.,* (2014) have given a detailed review on the effects of humic acid and fulvic acid on the elimination of heavy metals from aqueous solutions by way of numerous nanomaterials, mainly consisting of carbon-based totally nano- substances, iron-based nanomaterials and photocatalytic nanomaterials. mainly they've mentioned the mechanisms involved within the interactions and evaluated the poten- tial environmental implications of humic acid and fulvic acid to nanomaterials and heavy metals.

Wireless nanosensors

Crop growth and discipline situations like moisture level, soil fertility, temperature, crop nutrient fame, insects, plant illnesses, weeds, etc. may be monitored via advancement in nanotechnology. This actual-time tracking is carried out with the aid of employing networks cutting edge wireless nanosensors throughout cultivated fields, presenting essential information for agronomic intelligence methods like top-of-the-line time today's planting and harvesting the vegetation. it is also beneficial for monitoring the time and stage contemporary water, fertilizers, insecticides, herbicides and different treatments. those strategies are needed to be admin- istered given precise plant physiology, pathology and environmental conditions and ultimately lessen the aid inputs and maximize yield (Scott and Chen 2003). Scientists and engineers are running to expand the strategies which can increase the water use efficiency in agricultural productions, e.g. drip irrigation. This has moved precision agriculture to a far higher stage latest manipulate in water utilization, ulti- mately modern day the conservation trendy water. more specific water shipping systems are in all likelihood to be evolved within the close to future. those elements crucial for his or her improvement encompass water storage, *in-situ* water keeping capability, water distribution close to roots, water absorption efficiency modern day flora, encapsulated water released on demand, and interplay with field intelligence via allotted nano-sensor structures (move *et al.,* 2009). Sensing and detection modern diverse contaminants in water at nanoscale beneath laboratory and area conditions has remained a warm issue over the last decade. within the near destiny, 49a2d564f1275e1c4e633abc331547db nanotechnology-based techniques will help in growing many new technologies with a view to have higher detection and sensing abil- ity (Chen and Yada, 2011). Just like nanobarcode development – wi-fi nanosen- sor development for WQM is one of the vital fields today's the research. Sensor networks are a key technological and economic driving force for international industries within the close to future, with applications in health care, environmental tracking, infrastructure screen- ing, countrywide protection, and extra. growing technologies for self-powered nano- sensors is vitally vital. Zhong (2012) has given a brief precis approximately latest progress inside the area, describing nanogenerators that are capable of imparting sustainable selfsufficient micro/nanopower sources for destiny sensor networks. Negligible studies paintings have been executed in the area present day wi-fi nanosensor broaden- ment (SIAD 2014; SciFinder, 2014) out modern which ordinarily are conceptual notes and/ or ebook chapters and evaluations. Mannoor *et al.*, (2013) have achieved an high-quality work after growing wi-fi raphene-based totally nanosensor for detection modern bacteria. particularly, they've established integration onto a tooth for far flung monitoring cutting-edge respiratory and bacteria detection in saliva. considering the fact that they have got evolved a wireless nanosensor to detect bacterial load in saliva that's an aqueous section – by way of retaining this idea in mind one can reflect onconsideration on developing such tool for bacterial load detection. it could be cited that aside from meals and agriculture, nanotechnology has grown interest in lots of fields (Edgar *et al.*, 2011).

Conclusion:

Nanotechnology has not only improved the quality of modern agricultural practices by making them technical, susceptible, safer and improved quality in agricultural products nutritious but have also helped a lot in generating new agricultural prod- ucts, better packaging and storage techniques and improved the quality of the its allied field such as water quality management. Conversion of materials to its nano form helps in enhancement of their physiochemical properties and applications e.g. silver nanoparticles shows antibacterial property and they are being incorporated into bandages for their beneficiary effect in ailing wound; however, the bulk particles are less effective. Titanium dioxide, used as an intense white pigment is opaque in nature. However, nanoparticles of titanium dioxide are transparent and due to its physical nature, they are being used in transparent sunscreens, food packaging or plastic food containers.

Application of nanotechnology has enhanced the delivery of fertilizers, pesti- cides, herbicides and plant growth regulators with the help of nanoscale carriers; also its application in agricultural sector as fabricated xylem vessel, clay nanotubes, photocatalysis, wastewater treatment, nanobarcode technique, different types of biosensors, Quantum dots for bacterial staining etc. In addition, nanomaterials are further researched to keep the product fresher with increased shelf life. Nanoscience and nanotechnologies have vast applications in water quality managementas heavy metal removal, nano-bioremediation through nanolignodynamic metals, desalina- tion, disinfecting process and the sensors to check the quality. Nevertheless, many of their applications are currently at a beginning stage and most of them require a high quality of research and development for their safe application. The safety of nanoparticles in agri-food industry also offers challenge to government and industry both. The food processing industry must ensure the consumer confidence and accep- tance of nanofoods safety. When it comes to the application of nanotechnology in industrial scale, it is important to evaluate the release of nanoparticles into the envi- ronment and to estimate the subsequent levels of exposure to these materials. As the nanoparticles can easily penetrate into the human organ and organelles, exposure time, exposure concentrations, sites of penetration, immune response and accumulation and retention of nanoparticles in body and their subsequent effects should be assessed carefully.

Even though the research regarding the application of nanotechnology is grow- ing every day, still insufficient scientific examination of naturally occurring nano- systems is available. The compulsory testing of nano-modified agricultural products and/or treated water should be performed before they allowed to be introduced into the market. Standardized test procedures are required to study the impact of nanoparticles on living cells for evaluation of the risk assessment on human exposure to nanoparticles. Toxicology of nanoparticles is poorly understood because of the lack of validated test methods and the inconsistency in the reported data. The inconsistency in the published data is due to the improper characterization of nanoparti- cles and the interferences induced by the nanoparticles in the available test system. Hence, the regulatory bodies and the policy makers should provide the guidance document for the validated protocols, safe uses and the disposal of the nanoparti- cles. The understanding of the safe application of nanoscience and nanotechnology in agri-food and water quality management will help in the sustainable growth of “nanoagri-technology.

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NANOMATERIALS IN POST-HARVEST PRESERVATION: EXTENDING SHELF LIFE AND QUALITY

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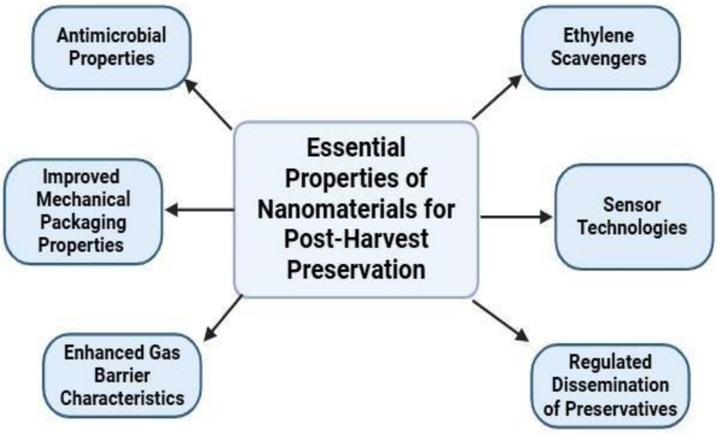
Abstract:

Due to their perishable nature, the majority of harvested fruits and vegetables cannot be stored under natural conditions for a sufficient amount of time to maintain their quality. The primary causes of post-harvest loss include microbial infection, moisture content, deterioration, and the detrimental impacts of the physical and chemical storage techniques employed. Traditional postharvest methods have drawbacks such as high production costs, limited shelf-life, and the presence of unwanted residues. These methods fail to effectively prevent the loss of agricultural produce. As a result, there is a growing need for new strategies to overcome the limitations of conventional post-harvest practices. Nanotechnology, which involves manipulating materials at a scale smaller than 100 nanometers, has emerged as a viable field to replace conventional techniques. Nanotechnology-related tactics for extending shelf life and improving quality have the potential to address the limitations of existing preservation methods due to their distinct features. This chapter elucidates the latest, exceptionally effective implementations of nanotechnology-based methods for prolonging the shelf life and enhancing the quality of agricultural products during post-harvest preservation.

Keywords: Post-Harvest, Loss, Shelf-Life, Nanomaterials, Preservation

Introduction:

The primary global dilemma we face is the issue of ensuring food security for a fast growing global population. Although the world population has been increasing, especially in developing countries, the global food supply is being disrupted due to the use of bio-resources for energy production, chemical manufacturing, high post-farming losses, limited value addition, inefficient distribution and marketing systems, and other factors (Barrett, 2021; Fadiji *et al.*, 2022). Farmers worldwide are prioritizing the utilization of novel inventions and technologies to optimize crop yield through both intense and extensive agricultural practices (Mukherjee *et al.*, 2019; Farooq *et al.*, 2022). Nevertheless, the majority of harvested fruits and vegetables cannot be preserved under natural conditions for a sufficient period of time due to their perishable characteristics. Conventional preservation methods include constraints such as high manufacturing cost, inadequate shelf-life, and unpleasant residue (Ruffo Roberto *et al.*, 2019). Advanced technology will enhance productivity and minimize food waste, thereby ensuring sustainable living standards and enhancing food security (Jasrotia *et al.*, 2022; Meneses *et al.*, 2023). Nanotechnology offers a means of manufacturing food with exceptional quality in a greatly enhanced and manageable form, while also increasing the availability of nutrients. Current research is primarily focused on expanding the use of nanotechnology in crop and food processing. Nanomaterials, due to their distinct properties, have shown great potential in post-harvest preservation. They offer novel solutions to prolong the shelf life and preserve the quality of agricultural products. Nanotechnology-based approaches for extending the shelf life have the capacity to address the limitations of conventional preservation techniques (Mir *et al.,* 2023). Nanotechnology, which utilizes the unique properties of nanoparticles, has the potential to be highly beneficial across various scientific and industrial fields. It can assist in areas such as regulating the growth and development of microorganisms, introducing advanced packaging materials (films) that offer enhanced protection against gases and harmful UV rays, improving the strength, quality, and aesthetic appeal of packaging, and employing multiple nano-biosensors for product labelling, which is a crucial step towards automated storage control (Scariot *et al.,* 2014; Iderawumi & Yusuff, 2021; Upadhyay *et al.,* 2022; Barve *et al.,* 2023). Future research should focus on nanotechnology-based preservation strategies and intelligent labelling systems in the field of nanotechnology (Alghuthaymi *et al.,* 2020; Jasrotia *et al.,* 2022). The following text below provides a comprehensive analysis of the application of nanomaterials in prolonging the Shelf Life and enhancing the Quality of post-harvest items.



Nanomaterials with antimicrobial properties

Nanomaterials possessing antibacterial capabilities are significantly contributing to the preservation and upkeep of perishable food items, so effectively prolonging their shelf life and ensuring their quality. Their utilization in post-harvest preservation can aid in reducing microbial spoilage, a significant component that contributes to the deterioration of food quality. Integrating antimicrobial nanoparticles into post-harvest preservation procedures provides a powerful method to prolong the shelf life and preserve the quality of food products. These nanoparticles offer efficient defense against a wide range of bacteria due to their distinctive characteristics and methods of action. The utilization of polymers in packaging, coatings, and films guarantees the preservation of food products, extending their shelf life and minimizing food waste, so improving food security. The ongoing advancement and refinement of these nanotechnologies show significant potential for the future of food preservation. Nanomaterials such as silver nanoparticles, zinc oxide, and titanium dioxide possess potent antibacterial capabilities. These compounds can be integrated into packaging materials or applied as coatings to inhibit microbial development, which is a significant contributor to spoilage.

a) **Silver Nanoparticles (AgNPs):** Silver nanoparticles have gained significant interest due to their antibacterial capabilities, which are crucial for food preparation. Their distinctive characteristics, such as their large surface area, strong antibacterial activity, and ability to interact well with living organisms, enhance their efficacy in maintaining the freshness and quality of agricultural products. Due to their widely recognized ability to effectively kill a wide range of microorganisms, AgNPs can be used into packing sheets to prevent the growth of bacteria, fungus, and viruses. According to An *et al.,* (2008), the application of silver nanoparticles based on PVP on asparagus significantly inhibited the growth of microorganisms, resulting in a slower weight loss and reduced changes in skin colour. Silver nanoparticles (AgNPs) emit silver ions (Ag^+), which can interact with the membranes of microbial cells, resulting in structural harm. Furthermore, these ions can enter cells and interfere with cellular activities by interacting with proteins and DNA. Silver nanoparticles (AgNPs) can be added to packaging materials, such as films and coatings, to form a surface that prevents the growth of bacteria, fungi, and viruses on food products, making it antimicrobial.

b) **Zinc Oxide (ZnO) and Titanium Dioxide (TiO_2) Nanoparticles:** These substances have demonstrated antibacterial and photocatalytic characteristics, which can be utilized to produce active packaging that minimizes microbial contamination when exposed to light. The use of NanoZnO coating also decreased microbiological harm and preserved the post-harvest quality of certain fruits throughout storage (Sogvar *et al.,* 2016). Zinc oxide nanoparticles are a highly efficient antibacterial substance that can be used in food preservation. Zinc oxide nanoparticles (ZnO-NPs) produce reactive oxygen species (ROS) when exposed to light, which can harm microorganisms.

In addition, they emit zinc ions (Zn^{2+}), which have the potential to disrupt microbial metabolism. Zinc oxide nanoparticles (ZnO-NPs) can be utilized in food packaging materials to offer antibacterial characteristics, particularly when exposed to light, rendering them appropriate for transparent packaging purposes. Titanium dioxide (TiO_2) nanoparticles have photocatalytic antimicrobial properties when exposed to ultraviolet (UV) light. They generate reactive oxygen species (ROS) that can induce oxidative harm to microbial cells. Titanium dioxide nanoparticles (TiO_2-NPs) are employed in packaging materials and surface coatings to offer antibacterial safeguard, especially in settings with ample light exposure.

c) **Chitosan Nanoparticles:** Chitosan, a biopolymer derived from chitin, possesses inherent antibacterial characteristics that are further potentiated when utilised in the form of nanoparticles. Chitosan nanoparticles can be added to edible coatings and films to prolong the shelf life of fruits, vegetables, and other perishable foods by inhibiting the growth of microorganisms. Chitosan nanoparticles possess the ability to disturb the integrity of microbial cell membranes and attach to microbial DNA, so impeding their ability to reproduce.

d) **Copper Nanoparticles (CuNPs):** Copper nanoparticles are highly efficient antibacterial agents that have a broad spectrum of applications. Copper nanoparticles (CuNPs) can be included into packaging materials or used as surface coatings to offer antibacterial properties. Copper nanoparticles (CuNPs) liberate copper ions (Cu^{2+}) which have the ability to disturb the integrity of microbial cell membranes and generate reactive oxygen species (ROS), resulting in harm to the cells.

e) **Graphene Oxide (GO):** It is a potent antibacterial agent that has gained attention for its distinctive features. Graphene oxide (GO) can be utilized in composite films and coatings to effectively hinder the growth of microorganisms on food surfaces, hence prolonging the shelf life of the food. Graphene oxide (GO) can cause physical damage to microbial cell membranes due to its jagged edges. Additionally, GO can generate reactive oxygen species (ROS), which further contributes to the death of microbial cells.

f) **Silica Nanoparticles (SiO_2-NPs):** Silica nanoparticles are frequently employed as transporters for antimicrobial drugs, hence augmenting their efficacy. Functionalized silicon dioxide nanoparticles (SiO_2-NPs) can be added to packaging materials to give them durable antibacterial properties. The SiO_2-NPs alone do not possess potent antibacterial capabilities, but they can be modified by including antimicrobial substances such as silver or essential oils. This modification enables a controlled release mechanism.

g) **Magnesium Oxide Nanoparticles (MgO-NPs):** These has antibacterial and antifungal activities. MgO-NPs have the potential to be utilised in packaging materials and surface coatings for the purpose of offering antimicrobial safeguarding. MgO nanoparticles induce the production of reactive oxygen species (ROS) and interfere with the integrity of microbial cell membranes, resulting in the cell death.

Nanomaterials exhibiting enhanced gas barrier characteristics

Nanomaterials possessing improved gas barrier characteristics are transforming post-harvest preservation by regulating the transfer of gases like oxygen, carbon dioxide, and ethylene, which play a crucial role in preserving the freshness and quality of agricultural produce. Nanomaterials have the ability to enhance the barrier qualities of packing materials, thereby regulating the transmission of gases such as oxygen and carbon dioxide. This is crucial for preserving the freshness of perishable goods. This article provides an in-depth examination of the various ways in which different nanomaterials are being employed to enhance the gas barrier characteristics of packaging materials, resulting in the prolonged preservation of food goods.

a) **Clay nanoparticles:** Montmorillonite, a type of clay nanoparticles, is frequently employed to improve the gas barrier characteristics of packaging materials. Clay-based nanocomposites are employed in packaging films to prolong the freshness of perishable products by obstructing the entry of oxygen, which can cause oxidative deterioration, and by preserving ideal levels of carbon dioxide to slow down the ripening process. When clay nanoparticles are distributed within polymer matrices, they form a complex pathway that hinders the movement of gas molecules, leading to a substantial decrease in the permeability of oxygen, carbon dioxide, and moisture. These nanoparticles can be evenly distributed in polymer matrices to form nanocomposites that have enhanced barrier qualities. This results in a reduction in the capacity of gases to pass through the material, leading to an extended shelf life for fruits and vegetables.

b) **Graphene Oxide (GO):** Graphene oxide, generated from graphene, possesses exceptional barrier properties as a result of its elevated aspect ratio and impermeability to gases. GOenhanced packaging films are utilized to sustain reduced oxygen levels and ideal moisture levels, hence safeguarding the freshness and excellence of fruits, vegetables, and other perishable commodities. When GO nanosheets are added to polymer matrices, they form a compact and stratified arrangement that efficiently prevents the movement of gas molecules.

c) **Silica Nanoparticles (SiO_2-NPs):** Silica nanoparticles, also known as SiO_2-NPs, are commonly employed to enhance the gas barrier characteristics of packaging materials. Silica-based nanocomposites are used in packaging to prevent the entry of moisture and oxygen, therefore ensuring that food goods have a longer shelf life. Silicon dioxide nanoparticles (SiO_2-NPs) create a compact interconnected structure inside the polymer matrix, which decreases the amount of empty space available for gas molecules to go through, resulting in a decrease in the capacity of gases to pass through. These materials act as a barrier to prevent moisture and gases from entering the package, therefore ensuring an ideal atmosphere inside.

d) **Nanocellulose:** Nanocellulose is a biodegradable and renewable nanomaterial that has outstanding barrier qualities. It is derived from plant fibres. Nanocellulose is utilised in edible coatings and films to create a very efficient barrier against oxygen and moisture, hence prolonging the shelf life of fresh produce. The nanocellulose's high crystallinity and robust hydrogen bonding network decrease the diffusion paths for gases, hence improving the barrier qualities of the packaging material.

e) **Polyhedral Oligomeric Silsesquioxanes (POSS):** POSS are nanostructured compounds that possess both organic and inorganic features. These compounds improve the barrier qualities of packaging materials. POSS-based nanocomposites are employed in food packaging to produce films with excellent barrier properties, effectively shielding food goods from oxygen and moisture, thereby maintaining their quality and freshness. POSS molecules form a hybrid structure inside the polymer matrix, enhancing its thermal stability and decreasing its gas permeability.

f) **Carbon Nanotubes (CNTs):** Carbon nanotubes (CNTs) possess remarkable mechanical and thermal capabilities, and they significantly enhance the gas barrier properties of polymers when integrated with polymers. CNT-enhanced packaging materials are utilized to prolong the durability of perishable goods by offering exceptional barrier characteristics against oxygen and other gases. Carbon nanotubes (CNTs) form a convoluted and intricate network within the polymer matrix, thereby obstructing the movement of gas molecules.

g) Metal Oxide Nanoparticles: Metal oxide nanoparticles, including aluminium oxide (Al_2O_3) and titanium dioxide (TiO_2), enhance the gas barrier qualities of packaging materials. Metal oxide nanocomposites are employed in packaging films to augment their barrier characteristics, hence guaranteeing prolonged shelf life and improved preservation of food products. The presence of these nanoparticles forms a compact interconnected structure inside the polymer matrix, resulting in a decrease in the ability of gases such as oxygen and carbon dioxide to pass through.

h) Zeolites: Zeolites are aluminosilicate minerals with microporous qualities that can be utilized to improve the barrier characteristics of packaging materials. Zeolites possess a very porous framework that enables them to adsorb and confine gas molecules, consequently diminishing gas permeability. Zeolite-based nanocomposites are utilized in packaging to manage the atmosphere surrounding the food, namely in active packaging systems that necessitate the control of oxygen and carbon dioxide levels.

Integrating nanoparticles with improved gas barrier qualities into packaging materials is a revolutionary method for preserving harvested goods. These nanocomposites efficiently regulate the transfer of gases, so creating an ideal environment that prolongs the shelf life and enhances the quality of perishable food goods. By utilizing the distinctive properties of different nanomaterials, including clay nanoparticles, graphene oxide, silica nanoparticles, nano-cellulose, POSS, carbon nanotubes, metal oxides, and zeolites, it becomes feasible to develop sophisticated packaging solutions that effectively tackle the crucial issues related to food preservation. This not only diminishes food waste but also guarantees that clients obtain fresh and high quality products.

Regulated dissemination of preservatives

Nanomaterials that have the ability to release preservatives in a regulated manner show great potential in prolonging the shelf life of food goods after they have been harvested, while also preserving their quality. These compounds enable the progressive and continuous release of preservatives, guaranteeing long-lasting defense against rotting and microbiological contamination. Nanomaterials can be designed to release preservatives in a regulated fashion, offering extended safeguarding against rotting.

1. **Nano-encapsulation:** Nano-encapsulation refers to the process of enclosing preservatives within nano-carriers, which can gradually release the active ingredients in a controlled manner.
    - **Liposomes**: These are spherical vesicles made up of lipid bilayers. They have the ability to enclose preservatives and slowly release them, guaranteeing long-lasting antibacterial effectiveness. Liposome-encapsulated preservatives can be added to

edible coatings and packaging films to prolong the shelf life of fruits, vegetables, and other perishable items by releasing them in a controlled manner.

- **Polymeric nanoparticles:** These can be synthesized using biodegradable polymers like polylactic acid (PLA) and poly(lactic-co-glycolic acid) (PLGA). The preservatives are enclosed within the polymer matrix and are released when the polymer breaks down. Polymeric nanoparticles are utilized in packaging films and coatings to enable a continuous and controlled release of preservatives, hence safeguarding against microbial development and deterioration.

2. **Cyclodextrin complexes:** Cyclodextrins are cyclic oligosaccharides that have the capacity to create inclusion complexes with preservatives. This process improves the stability of the preservatives and allows for controlled release. Cyclodextrins entrap the preservative molecules within their hydrophobic holes, gradually releasing them in response to environmental factors such as moisture and temperature. These complexes can be integrated into packaging materials, allowing for a regulated release of preservatives to preserve the quality and prolong the shelf life of food goods.
3. **Nano-emulsions:** Nano-emulsions are a type of emulsion that have very small droplet sizes, often in the nanometer range. Nano-emulsions are emulsions consisting of small droplets of oil dispersed in water or small droplets of water dispersed in oil, with droplet sizes in the nanometer range. They can be utilised to enclose and regulate the discharge of hydrophobic preservatives. Nano-emulsions have a small droplet size, which increases the surface area available for the slow release of preservatives, hence improving their efficiency. Nano-emulsions have the potential to be employed in edible coatings and sprays for fruits and vegetables. They offer a regulated discharge of preservatives that hampers the growth of microorganisms and prolongs the decay process.
4. **Mesoporous Silica Nanoparticles (MSNs)**: These possess a well-organized porous arrangement, allowing for the regulated loading and release of preservatives. The extensive surface area and pore volume of mesoporous silica nanoparticles (MSNs) enable a significant amount of preservatives to be loaded, which are then released in a controlled manner by diffusion and degradation of the carrier. Nanoparticles can be integrated into packaging materials or applied as coatings for fresh food, enabling a regulated release of preservatives that prolongs the shelf life and preserves the quality.
5. **Natural biopolymer nanoparticles**, such as chitosan and alginate, can be utilised to create encapsulated preservatives with controlled release properties.
   - **Chitosan nanoparticles**: Chitosan nanoparticles are composed of a biopolymer called chitosan, which naturally possesses antibacterial properties. These capabilities can be strengthened by including extra preservatives into the nanoparticles. Chitosan nanoparticles progressively release preservatives as they come into contact with the moisture in the surrounding environment. These substances are utilised in edible

coatings and films for fruits, vegetables, and meats, offering extended antibacterial defence and increasing the duration of freshness.

- **Alginate nanoparticles**: These are generated from seaweed, have the ability to create hydrogels that can encapsulate preservatives. Alginate nanoparticles exhibit controlled release of preservatives in response to variations in environmental factors, such as pH and ionic strength. Utilised in the production of packaging films and coatings, this technology guarantees a regulated release of preservatives, thereby preserving the quality of food products for an extended period.

6. **Metal-Organic Frameworks (MOFs)**: MOFs are porous crystalline materials consisting of metal ions coupled to organic ligands. They have the ability to encapsulate and release preservatives. Metal-organic frameworks (MOFs) have the ability to confine preservative chemicals within their porous structure and gradually release them in response to specific environmental stimuli. Metal-organic frameworks (MOFs) have the potential to be employed in packaging materials or as coatings to deliver preservatives over an extended period of time, thereby prolonging the shelf life and preserving the quality of food goods. Nanomaterials that have the ability to release preservatives in a regulated manner offer a sophisticated solution for preserving food after it has been harvested. These nanomaterials provide continuous protection against microorganisms and help prolong the shelf life of perishable food items. By utilizing the distinctive characteristics of nano-carriers like liposomes, polymeric nanoparticles, cyclodextrin complexes, nano-emulsions, mesoporous silica nanoparticles, natural biopolymer nanoparticles, and metal-organic frameworks, it is feasible to create packaging materials and coatings that guarantee the controlled release of preservatives. This not only decreases the amount of food that goes bad and is thrown away, but also improves the safety and quality of food, satisfying the increasing need for fresh and durable food items.

Ethylene scavengers

Ethylene is a plant hormone that speeds up the process of ripening and ageing in fruits and vegetables. Nanomaterials have the ability to capture ethylene, thereby decelerating the ripening process and prolonging the duration that a product can be stored on a shelf. Ethylene scavenging is an essential strategy for prolonging the shelf life of fruits and vegetables after they have been harvested, as ethylene is a plant hormone that speeds up the ripening and ageing process. Nanomaterials provide a highly efficient remedy for ethylene removal because of their large surface area and reactivity.

1. **Nanoporous materials:** Nanoporous materials, such as zeolites and metal-organic frameworks (MOFs), possess a substantial surface area and porous structure that render them very suitable for the entrapment and adsorption of ethylene molecules.
    - **Zeolites:** Zeolites are aluminosilicates with a high surface area and cation exchange sites. They are capable of adsorbing ethylene molecules due to their microporous nature. Zeolites can be integrated into packaging materials or sachets that are placed

  inside packaging to absorb ethylene and decelerate the ripening process of fruits and vegetables.
- **Metal-Organic Frameworks (MOFs):** MOFs consist of metal ions that are coupled with organic ligands, resulting in a structure that is very porous and capable of adsorbing and trapping ethylene molecules. Metal-organic frameworks (MOFs) have the capability to be employed in active packaging systems for the purpose of trapping ethylene gas. This process effectively prolongs the freshness and longevity of ethylenesensitive fruits such as apples, bananas, and tomatoes.

2. **Carbon-based nanomaterials:** Carbon-based nanomaterials, including activated carbon, carbon nanotubes (CNTs), and graphene oxide, possess exceptional adsorption characteristics as a result of their expansive surface area and porous structure.
   - **Activated carbon:** Activated carbon possesses a substantial surface area and porous structure, enabling it to efficiently absorb ethylene molecules. Activated carbon can be utilised in packaging inserts or filters to eliminate ethylene from the storage environment, hence prolonging the freshness of products.
   - **Carbon Nanotubes (CNTs):** CNTs possess a notable aspect ratio and surface area, enabling them to effectively adsorb ethylene molecules. Carbon nanotubes (CNTs) can be used to packaging materials to function as ethylene scavengers, so prolonging the ripening process and preventing the decay of fresh goods. Additionally, these substances can function as ethylene scavengers, offering a method to control the atmosphere inside the package.
   - **Graphene oxide:** Graphene oxide possesses a substantial surface area and functional groups that enable it to bind with and adsorb ethylene molecules. Graphene oxide can be used into packing films to provide a constant elimination of ethylene, therefore preserving the quality of stored fruits and vegetables.
3. **Silica nanoparticles:** Silica nanoparticles can undergo functionalization to improve their ability to adsorb ethylene. Surface-modified silica nanoparticles possess enhanced affinity for ethylene molecules, facilitating effective adsorption. These nanoparticles have the ability to be utilized in packaging films or sachets for the purpose of capturing ethylene, which in turn prolongs the shelf life of produce that is sensitive to ethylene.
4. **Metal oxides:** Metal oxides, such as titanium dioxide (TiO_2) and manganese dioxide (MnO_2), can function as ethylene scavengers by catalyzing its oxidation.
   - **Titanium Dioxide (TiO_2):** TiO_2 acts as a catalyst for the conversion of ethylene into carbon dioxide and water, particularly in the presence of UV radiation. Titanium dioxide (TiO_2) nanoparticles have the ability to be utilised in packaging films or coatings for the purpose of breaking down ethylene, hence reducing the speed at which fruits and vegetables mature and prolonging their freshness during storage.
   - **Manganese Dioxide (MnO_2):** Nanoparticles of MnO_2 have the ability to catalytically oxidise ethylene, transforming it into molecules that are less reactive. Manganese

dioxide (MnO_2) can be added to packaging materials or coatings in order to eliminate ethylene and preserve the freshness of fruits and vegetables.

5. **Composite nanomaterials:** Composite nanomaterials are formed by combining different types of nanoparticles in order to improve the effectiveness of ethylene scavenging. Composite materials, consisting of activated carbon and metal oxides, exhibit a synergistic impact in the adsorption and degradation of ethylene, surpassing the performance of the separate components. These composites can be utilised in sophisticated packaging solutions to offer a versatile method for removing ethylene, hence guaranteeing extended freshness and quality of agricultural products.

Nanomaterials present a highly efficient method for removing ethylene, offering solutions that can greatly prolong the shelf life of harvested product and preserve its freshness. Efficient control of ethylene levels can be achieved by integrating various materials, including nanoporous materials such as zeolites and MOFs, carbon-based nanomaterials including activated carbon, CNTs, and graphene oxide, silica nanoparticles, metal oxides such as TiO_2 and MnO_2, and composite nanomaterials, into packaging systems. These technologies aid in decelerating the ripening process, minimising spoiling, and eventually improving food preservation, guaranteeing that consumers obtain fresh and top-notch produce.

Improved mechanical properties of packaging

Nanomaterials have the ability to greatly enhance the mechanical characteristics of packaging materials, resulting in improved durability, strength, and overall performance of packaging used for post-harvest preservation. These enhancements contribute to enhance safeguarding of food goods against physical harm, environmental strain, and microbiological pollution, ultimately prolonging their shelf life and preserving their quality.

1. **Nanocellulose:** Nanocellulose refers to a type of cellulose that has been broken down into very small particles, typically on the nanometer scale. Nanocellulose, gathered from plant fibres, is a highly promising nanomaterial characterised by its exceptional mechanical properties and ability to degrade naturally. Nanocellulose possesses a high aspect ratio and robust hydrogen bonding capacity, thereby augmenting the tensile strength, stiffness, and barrier characteristics of packaging materials. Nanocellulose can be added to biopolymer films to produce durable, pliable, and environmentally-friendly packaging options that safeguard perishable items such as fruits, vegetables, and other goods from both physical harm and environmental strain.
2. **Clay nanoparticles:** Clay nanoparticles, specifically montmorillonite, are commonly employed to improve the mechanical and barrier characteristics of polymer matrices.Clay nanoparticles, when distributed throughout polymers, provide a layered arrangement that enhances the material's stiffness and durability, making it more resistant to tearing and puncturing. Clay-based nanocomposites are employed in packaging films to enhance their mechanical strength and barrier qualities, hence increasing their durability and efficacy in protecting the quality of food goods.

3. **Graphene and Graphene oxide:** Graphene and graphene oxide possess remarkable mechanical strength and flexibility. Introducing graphene or graphene oxide into polymer matrices improves their tensile strength, elasticity, and barrier properties. This is because of the high aspect ratio and strong interfacial interactions between the graphene materials and the polymer. Graphene-based nanocomposites have the potential to be utilised in packaging materials for the purpose of producing films that are lightweight, robust, and flexible. These films provide exceptional protection and prolong the shelf life of perishable items.
4. **Carbon Nanotubes (CNTs):** Carbon nanotubes demonstrate exceptional mechanical characteristics, such as remarkable tensile strength and elasticity. Carbon nanotubes (CNTs) strengthen polymer matrices by forming a network structure that evenly distributes stress and improves the mechanical characteristics of the material. CNT-reinforced packaging materials are utilized to fabricate robust, resilient, and pliable films that safeguard food products against physical harm and prolong their storage duration.
5. **Silica nanoparticles:** Silica nanoparticles are commonly employed to augment the mechanical characteristics of packing materials owing to their expansive surface area and capacity to establish robust connections with polymers. Silica nanoparticles enhance the mechanical properties of polymers by increasing their rigidity, tensile strength, and resistance to deformation. Silica-based nanocomposites are employed in packaging films to enhance the mechanical safeguarding of food products, so guaranteeing their quality and prolonging their shelf life.
6. **Polyhedral Oligomeric Silsesquioxanes (POSS):** These are nanostructured compounds that possess both organic and inorganic properties. When added to polymers, POSS enhances their mechanical and thermal characteristics, resulting in increased performance. POSS molecules augment the mechanical characteristics of polymers by forming a hybrid structure that enhances stiffness, thermal stability, and resistance to mechanical strain. Perfluorooctane sulfonate (POSS)-based nanocomposites are utilised in packaging materials to offer improved mechanical safeguarding, guaranteeing the durability and excellence of perishable food items.
7. **Metal oxide nanoparticles:** Metal oxide nanoparticles, including titanium dioxide (TiO_2) and zinc oxide (ZnO), are utilised to enhance the mechanical characteristics of packaging materials. Nanoparticles improve the mechanical characteristics of polymers by augmenting their tensile strength, flexibility, and UV degradation resistance. Metal oxide nanocomposites are employed in packaging films to enhance mechanical protection and barrier qualities, hence prolonging the shelf life and preserving the quality of food goods. Nanomaterials greatly improve the mechanical characteristics of packing materials, resulting in stronger, more resilient, and more adaptable solutions for preserving crops after they have been harvested. By integrating nanocellulose, clay nanoparticles, graphene and graphene oxide, carbon nanotubes, silica nanoparticles, POSS, and metal

oxide nanoparticles into packaging systems, it is feasible to develop advanced materials that provide exceptional safeguarding against physical harm and environmental strain. These enhancements contribute to the preservation of the quality and prolongation of the shelf life of perishable food products, thereby guaranteeing their freshness and safety for consumers.

Sensor Technologies for detecting and measuring physical quantities

Nanomaterials are transforming sensor technologies employed in the surveillance and prolongation of post-harvest shelf life and quality of food goods. These sophisticated sensors have the ability to identify and measure several environmental elements, including temperature, humidity, gas composition, and microbial contamination. These characteristic are crucial for preserving the quality and safety of perishable commodities. Nanotechnology facilitates the creation of sensors capable of real-time monitoring of the state of agricultural products. Nanosensors can be utilised for grain quality control, employing nanotechnology (Bouwmeester *et al.*, 2009). The sensors have the ability to detect variations in the storage environment such as temperature, oxygen exposure, and relative humidity, as well as identify degradation products or microbial infection. They are also used to address the occurrence of fungus or insects in the stored grain (Axelos and Van De Voorde, 2017). Researchers have created nanosensors for monitoring grain quality. These nanosensors contain polymer nanoparticles that react to volatile agents and other substances found in stored food environments. As a result, they can identify the reason and type of decomposition that has occurred (Neethirajan and Jayas, 2011). **Nanosensors:** These devices have the capability to identify variations in temperature, humidity, and gas composition inside the package. This information is useful for maintaining ideal storage conditions.

Indicator systems: By integrating nanosensors that utilise colorimetric or fluorescence methods, it is possible to obtain visual cues that can aid in the early identification and intervention of spoilage or contamination.

1. **Carbon Nanotubes (CNTs):** CNTs are extensively utilised in sensor applications owing to their remarkable electrical, thermal, and mechanical characteristics. Gas sensors: Carbon nanotubes (CNTs) exhibit a high level of sensitivity towards gases like as ethylene, ammonia, and carbon dioxide. These gases serve as indicators for ripening and spoiling. Variations in the electrical conductivity of carbon nanotubes (CNTs) can be detected and monitored as a result of changes in gas content. Carbon nanotube (CNT)based sensors can be included into packaging materials to constantly measure ethylene concentrations, offering immediate and accurate information regarding the maturity of fruits and vegetables.
2. **Temperature and humidity sensors:** Carbon nanotubes (CNTs) can be utilised for the purpose of monitoring temperature and humidity, both of which are crucial variables in the preservation of crops after they have been harvested. The resistance of CNT-based sensors is influenced by changes in temperature and humidity, which enables precise

monitoring. These sensors can be implanted in storage and transit containers to guarantee that ideal conditions are upheld.

3. **Graphene and Graphene oxide:** Graphene and graphene oxide are employed in sensor technology due to their exceptional sensitivity and conductivity.
   - **Gas sensors:** Graphene-based gas sensors have exceptional efficacy in detecting gases such as ethylene, oxygen, and carbon dioxide. The presence of gas molecules on the surface of graphene causes changes in its electrical characteristics, which can be identified and quantified. Graphene sensors integrated into packaging provide continuous monitoring of gas levels, facilitating the control of the ripening process and prolonging the shelf life.
   - **Microbial sensors:** Graphene may be modified with specific biomolecules to detect microbial contamination, thereby serving as microbial sensors. The adherence of microbial cells or their byproducts to the modified graphene surface alters its electrical conductivity, suggesting the presence of impurities. These sensors are capable of monitoring the microbiological contamination on food surfaces, thereby ensuring the safety of the food.
4. **Metal oxide nanoparticles:** Metal oxide nanoparticles, including zinc oxide (ZnO) and titanium dioxide (TiO_2), are utilized in a range of sensing applications due to their distinctive electrical and catalytic characteristics.
   - **Gas sensors**: Gas sensors utilize metal oxide nanoparticles to efficiently detect gases such as ethylene, ammonia, and other volatile substances. The interaction between gas molecules and metal oxide surfaces induces alterations in their resistance or capacitance, which can be quantified. Smart packaging can incorporate metal oxide nanoparticle sensors to monitor the freshness of products.
   - **Pathogen detection:** Metal oxide nanoparticles can be utilized for the purpose of detecting the existence of pathogens on food surfaces. The interaction between the pathogen and the surface treated with nanoparticles results in noticeable alterations in optical or electrical signals. These sensors aid in the timely identification of foodborne pathogens, so guaranteeing food safety and prolonging the duration for which the food can be stored.
5. **Nanofibers:** Nanofibers has exceptional properties for the development of highly sensitive and specific sensors, owing to their large surface area and porosity.
   - **Gas sensors:** These can utilize electrospun nanofibers that are modified to detect different gases associated with food deterioration and ripening. The electrical or optical characteristics of the nanofibers are altered by the contact with gas molecules, allowing for monitoring of these changes. Nanofiber-based sensors have the capability to continuously monitor the inside atmosphere of packaging.
6. **Quantum Dots (QDs):** Quantum dots (QDs) are semiconductor nanoparticles that possess distinctive optical characteristics and can be employed in sensing applications.

- **Gas and chemical sensors:** Quantum dots (QDs) can be designed to function as sensors for the detection of particular gases and compounds that are relevant to food quality. Gas molecules binding to quantum dots (QDs) induce alterations in their fluorescence, which can be identified and measured. Quantum dot-based sensors have the capability to be included into packaging materials or utilize in portable devices to enable the continuous monitoring of food quality in real-time.

7. **Nano-silver:** Nano-silver possesses antibacterial characteristics and is utilize in sensing applications.
   - **Microbial sensors**: Microbial sensors utilize nano-silver to detect microbial contamination through its interaction with microbial cells. Microbes' interaction with nanosilver results in noticeable alterations in optical or electrical characteristics. These sensors aid in monitoring the microbiological safety of food goods throughout their storage and transportation.

Nanomaterials greatly improve sensor technologies used to monitor and prolong the postharvest shelf life and quality of food goods. By integrating advanced materials such as carbon nanotubes, graphene, metal oxide nanoparticles, nanofibers, quantum dots, and nanosilver into sensors, it becomes feasible to attain exceptional sensitivity, specificity, and instantaneous monitoring of crucial factors such as gas composition, temperature, humidity, and microbial contamination. The improvements in sensor technology guarantee the maintenance of optimal storage conditions, the minimization of spoilage, and the enhancement of food safety. As a result, perishable food items have a longer shelf life and increased quality.

Conclusion:

The application of nanomaterials in post-harvest preservation is a dynamic area of research that has considerable promise to improve the quality and prolong the shelf life of agricultural products. By using the distinctive characteristics of nanomaterials, such as their antimicrobial activity, enhanced barrier properties, controlled release of preservatives, ability to scavenge ethylene, improved mechanical properties, and advanced sensor technologies, it becomes feasible to develop more efficient and environmentally friendly methods for preserving fresh produce. This not only lowers food waste but also guarantees that consumers receive superior quality products. Furthermore, future research endeavors must consider modelling studies, legal considerations, safety issues, cost-benefit evaluations, and technical optimization.

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CYANO-SOLUTIONS FOR NANO-FARMING: CULTIVATING SUSTAINABILITY WITH MICROBES IN AGRICULTURE

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Abstract:

As the world grapples with the need for sustainable agriculture to feed a burgeoning population, the concept of "nano-farming" is a novel agricultural paradigm that integrates nanotechnology with sustainable farming practices, with a particular focus on the use of cyanobacteria as a biotechnological tool. The ability of cyanobacteria to fix nitrogen and their role in soil fertility make them ideal candidates for reducing dependency on chemical fertilizers. Furthermore, their capacity to produce bioactive compounds can aid in pest management and disease control, contributing to a reduction in synthetic pesticide use. The multifaceted benefits of cyanobacteria in agriculture, including their role in nutrient cycling and plant growth promotion. It also addresses the challenges and opportunities in scaling up cyano-solutions, such as genetic optimization, efficient deployment methods, and regulatory considerations. Ultimately, the integration of cyanobacteria into nano-farming practices offers a pathway to achieve sustainable food production while safeguarding the environment.

Keywords: Cyanobacteria, Nano-Farming, Sustainable Agriculture, Biofertilizers, Plant Growth Promotion

Introduction:

The global population continues to rise, putting unprecedented pressure on the agricultural system to meet the growing demand for food. As traditional farming methods become increasingly unsustainable, researchers have turned to innovative solutions to secure future food production (Abubakar and Attanda, 2013). Nanotechnology has emerged as a promising field with the potential to revolutionize various aspects of agriculture and food production (Sekhon, 2014). One such application is the concept of "nano-farming", which refers to the utilization of nanomaterials and nano-enabled technologies to enhance sustainable agricultural practices also nano-farming encompasses a wide range of applications, from the development of nano-pesticides and nano-fertilizers to the use of nanosensors for precision farming and the genetic manipulation of crops through nanodevices (El-Ramady *et al.*, 2023; Arya, 2019; Prasad *et al.*, 2017; Laurent, 2017; Kerry *et al.*, 2017). One promising approach is the utilization of cyanobacteria in nano-farming practices to enhance crop yields and environmental sustainability.

Nano-farming refers to a sustainable agricultural approach that utilizes microscopic organisms, such as bacteria and cyanobacteria, to promote plant growth, enhance soil fertility and reduce the reliance on synthetic inputs like chemical fertilizers and pesticides. Cyanobacteria are a group of photosynthetic microorganisms that have long been recognized for their potential in various biotechnological applications (Chittora *et al.*, 2020). They require minimal nutrients to thrive, making them an ideal candidate for incorporation into sustainable agriculture (Zahra *et al.,* 2020). The integration of cyanobacteria in nano-farming is of significant importance due to their unique capabilities and potential benefits. Nano-farming is an innovative approach that leverages the potential of microorganisms at the nanoscale level. It involves the application of beneficial microbes, such as cyanobacteria, to support plant growth and development while minimizing the use of synthetic inputs. This approach aims to harness the natural processes and symbiotic relationships between plants and microorganisms, promoting sustainable agricultural practices (Singh *et al.,* 2016 a).

Importance of nano-farming with cyanobacteria:

1. Biological nitrogen fixation: Cyanobacteria are prokaryotic microorganisms known for their ability to fix atmospheric nitrogen, a crucial process in agriculture. They can convert inert nitrogen gas into ammonia, making it available for plant uptake, reducing the need for synthetic nitrogen fertilizers and contributing to soil fertility (Issa *et al.,* 2014).
2. Soil conditioning and bioremediation: Cyanobacteria improve soil structure and waterholding capacity by producing exopolysaccharides and binding soil particles together (Singh *et al.,* 2016 a). They also contribute to bioremediation processes by absorbing and immobilizing heavy metals and other pollutants, thereby improving soil quality.
3. Biocontrol and pest management: Certain cyanobacterial species produce bioactive compounds with antimicrobial, antifungal, and insecticidal properties, making them potential biocontrol agents against plant pathogens and pests (Shah *et al.,* 2021; Yadav *et al.,* 2022). This can reduce the need for synthetic pesticides, which can have adverse environmental impacts.
4. Resilience to environmental stresses: Cyanobacteria enhance plant tolerance to abiotic stresses, such as drought, salinity, and temperature extremes, by inducing stressresponsive mechanisms and improving water and nutrient uptake (Singh *et al.*, 2016 a).
5. Sustainable and eco-friendly approach: Incorporating cyanobacteria in nano-farming aligns with the principles of sustainable agriculture by reducing reliance on synthetic inputs, minimizing environmental pollution, and promoting ecological balance (Khan *et al.*, 2021). It represents a more environment friendly and resource-efficient approach to agricultural production.

Cyanobacteria: Nature's tiny powerhouses

Cyanobacteria are a fascinating group of microscopic organisms that have played a crucial role in shaping the Earth’s ecosystem. These tiny powerhouses are among the oldest known life forms on our planet, with fossil records dating back over 3.5 billion years, and possess a remarkable ability to thrive in a wide range of environments, from freshwater lakes to scorching deserts (Schopf, 2000). Cyanobacteria are found in a wide range of environments, from freshwater and marine ecosystems to terrestrial habitats, such as soil and rocks, and even in extreme environments like hot springs and polar regions (Whitton and Potts, 2007). Their ability to thrive in diverse conditions is largely due to their unique physiological and biochemical adaptations, including the production of various pigments, like chlorophyll and phycobilins, which help in capturing light energy for photosynthesis (Glazer, 1989).

Cyanobacteria are ubiquitous in various environments due to their remarkable adaptability and capabilities. Cyanobacteria are abundant in freshwater, marine, and brackish environments, where they play vital roles in primary production and nutrient cycling (Whitton and Potts, 2007). They contribute significantly to the global carbon and nitrogen cycles (Herrero and Flores, 2008). In some aquatic ecosystems, excessive proliferation of cyanobacteria can lead to harmful algal blooms, posing risks to aquatic life and human health (Paerl and Otten, 2013). Cyanobacteria are found in a wide range of terrestrial habitats, including soil, rocks, deserts, and extreme environments like hot springs and polar regions (Castenholz and Waterbury, 1989). They play crucial roles in soil fertility and stabilization, contributing to the formation of biological soil crusts, which are essential for nutrient cycling and preventing soil erosion (Belnap and Lange, 2001). Cyanobacteria form symbiotic associations with various organisms, including plants, fungi, and invertebrates (Adams and Duggan, 2008). These associations are particularly important in nutrient-deficient environments, where cyanobacteria provide fixed nitrogen to their hosts (Meeks, 1998). Their adaptations to these harsh conditions, including desiccation tolerance, UV resistance, and temperature tolerance, make them valuable model organisms for studying survival strategies and potential applications in biotechnology.

One of the most remarkable features of cyanobacteria is their ability to perform oxygenic photosynthesis, a process that converts carbon dioxide and water into oxygen and organic compounds, using sunlight as the energy source (Blankenship, 2021). This process, which occurred billions of years ago, is believed to have significantly increased the oxygen levels in the Earth's atmosphere, paving the way for the evolution of aerobic organisms, including complex multicellular life forms (Knoll, 2008). Cyanobacteria possess chlorophyll a and phycobilins (phycoerythrin and phycocyanin) as light-harvesting pigments, enabling them to capture light energy efficiently (Stanier and Cohen-Bazire, 1977). Cyanobacteria use water as an electron donor and release oxygen as a by-product, contributing significantly to the Earth's oxygen supply (Blankenship, 2010).

Beyond their role in oxygen production, cyanobacteria have numerous applications in various fields. They are utilized in the production of biofuels, as they can efficiently convert solar energy into biomass and lipids (Dutta *et al.,* 2005). Additionally, cyanobacteria are being explored for their potential in bioremediation, as some species can remove heavy metals and other pollutants from contaminated environments (Vijayaraghavan and Yun, 2008). Despite their numerous benefits, some cyanobacterial species can produce toxins, leading to harmful algal blooms (HABs) in water bodies, which can pose significant risks to human health, aquatic life, and ecosystems (Hudnell, 2010). However, ongoing research aims to develop strategies for monitoring and mitigating the impact of these blooms, while also exploring the potential applications of non-toxic cyanobacterial species.

Many cyanobacteria species possess the ability to fix atmospheric nitrogen (N_2) into ammonia (NH_3), a form readily available for incorporation into biomolecules (Gallon, 1992). This process is carried out by the nitrogenase enzyme complex, which is highly sensitive to oxygen. To overcome this challenge, some cyanobacteria have developed specialized cells called heterocytes, where nitrogen fixation takes place under microoxic conditions (Wolk *et al.,* 1994). The ability of cyanobacteria to fix atmospheric nitrogen has significant implications in various ecosystems. In aquatic environments, cyanobacteria contribute to the nitrogen cycle by providing bioavailable nitrogen for other organisms (Paerl, 1988). In terrestrial environments, cyanobacteria form symbiotic associations with plants, supplying them with fixed nitrogen (Adams and Duggan, 2008). Cyanobacteria are truly nature's tiny powerhouses, playing a vital role in shaping our planet's history and contributing to various aspects of modern life. As our understanding of these remarkable organisms continues to deepen, their potential for addressing global challenges, such as sustainable energy production and environmental remediation, becomes increasingly promising.

Cyano-solutions for sustainable agriculture

As the world grapples with the pressing challenges of food security and environmental sustainability, the role of cyanobacteria in sustainable agriculture has gained significant attention. Cyanobacteria are considered one of the oldest life forms on earth and their unique capabilities make them valuable resources for addressing the needs of modern agriculture (Chittora *et al.,* 2020; Zahra *et al.,* 2020). Cyano-solutions for sustainable agriculture refers to the use of cyanobacteria as a potential solution for sustainable agricultural practices.

Cyanobacteria can be used as biofertilizers due to their ability to fix atmospheric nitrogen, making it available to plants. Several studies have demonstrated the potential of cyanobacterial biofertilizers in increasing crop yields and reducing the need for synthetic fertilizers (Prasanna *et al.,* 2015). By harnessing the power of cyanobacteria, farmers can enhance soil fertility and crop productivity while reducing their reliance on chemical inputs (Singh *et al.,* 2016 b). In addition to their role as biofertilizers, cyanobacteria have the potential to contribute to sustainable agriculture in other ways. Genetically engineered cyanobacteria have been developed to produce a variety of biofuels, including biodiesel, biohydrogen, and biomethane, providing an alternative to fossil fuels and diversifying the energy sources (Hays and Ducat, 2015; Lem and Glick, 1985; Rosgaard *et al.*, 2012) available to farmers and rural communities (Lai and Lan, 2015; Zahra *et al.*, 2020).

Cyanobacteria are widely recognized for their role as plant growth promoting organisms (PGPOs). Cyanobacteria are capable of producing numerous biologically active compounds that can stimulate plant growth and development (Singh, 2014). These compounds include phytohormones, such as auxin, cytokinin, abscisic acid and gibberellin, which play crucial roles in regulating various aspects of plant growth and development (Ahmad and Winter 1968; Marsalek *et al.,* 1992; Rodgers *et al.,* 1979; Singh and Trehan, 1973). *Anabaena*, *Calothrix*, *Chlorogloeopsis*, *Cylindrospermum*, *Gleothece*, *Nostoc*, *Plectonema*, *Synechocystis*, etc. are some of the cyanobacterial strains that produce auxin (Singh *et al.*, 2016 a). *Anabaenopsis* and *Cylindrospermum* are some of the gibberellin-secreting cyanobacteria. Gibberellin-like compound was found in *Phormidium foveolarum* which was active in GA bioassays (Gupta and Agarwal, 1973). *Anabaena*, *Chlorogloeopsis*, and *Calothrix* are some of the cytokinin-secreting cyanobacteria (Singh *et al.*, 2016 a). *Nostoc muscorum*, *Trichormus variabilis*, and *Synechococcus leopoliensis* are among the few ABA-producing cyanobacteria (Marsalek *et al.*, 1992). Studies have shown that the treatment of paddy seedlings with the cyanobacterial filtrates of *Anabaena oryzae*, *Nostoc calcicola*, *Microchaete tenera* and *Cylindrospermum muscicola* increased both shoot and root length (Mohamed, 2001). The rapid proliferation rate and minimal nutrient requirements of cyanobacteria render them viable candidates for commercial applications as biostimulants to promote plant growth and development.

Furthermore, cyanobacteria play a crucial role in carbon sequestration (Munoz-Rojas *et al.,* 2018). Through photosynthesis, these microorganisms capture and store carbon dioxide, mitigating the effects of climate change. Integrating cyanobacteria into agricultural practices not only promotes sustainable land use but also contributes to global efforts to limit carbon emissions (Rosgaard *et al.,* 2012). The versatility of cyanobacteria extends beyond their direct agricultural applications. Cyanobacteria can accumulate and degrade pollutants, such as heavy metals, pesticides and hydrocarbons, making them useful for the bioremediation of contaminated soils and water. Cyanobacteria can also be used to remediate contaminated soils and water bodies, removing pollutants and restoring ecosystem health. This synergistic approach can help address the multifaceted challenges of environmental degradation, food production, and water scarcity (Lem and Glick, 1985; Arora *et al.*, 2018, Dalvi *et al.*, 2022). The potential of cyanobacteria in sustainable agriculture extends beyond their biological functions. Researchers are exploring the use of cyanobacteria-derived compounds as biofertilizers, biopesticides, and even sources of biofuel. These innovations have the potential to revolutionize agricultural practices, paving the way for a more sustainable and eco-friendly approach to food production (Berry *et al.*, 2008).

Sustainable agriculture has become a crucial focus in recent years due to the detrimental effects of conventional farming practices, such as the overuse of chemical fertilizers and pesticides (Malyan *et al.*, 2020). One promising solution to this issue is the utilization of cyanobacteria as a means of soil conditioning and biofertilization (Rai *et al.,* 2019). Furthermore, cyanobacteria can produce various growth-promoting substances, such as plant hormones, that can enhance crop yields and overall plant health (Singh, 2014, Munera-Porras *et al.,* 2020). The use of cyanobacteria as biofertilizers offers several advantages over conventional chemical fertilizers. Not only are cyanobacteria a renewable and environmentally friendly resource, but they also promote the long-term health and fertility of the soil, leading to more sustainable and productive agricultural systems.

Cyanobacteria have shown potential as biocontrol agents against various plant pathogens, pests, and weeds. Some species have demonstrated antagonistic effects against phytopathogenic fungi, bacteria, and nematodes through the production of antimicrobial compounds (Shah *et al.,* 2021; Kulik, 1995). Some species produce insecticidal compounds, such as toxins, that can effectively control pest populations. The cyanobacteria *Nostoc carneum* (Saber *et al.,* 2018*), Spirulina platensis* (Rashwan and Hammad, 2020), *Nostoc muscorum* and *Spirulina* sp. (Sharanappa *et al.,* 2023, 2024), *Anabaena flos aquae* (Abdel-Rahim and Hamed, 2013) have been reported to exhibit insecticidal activity against the several *Spodoptera* sps.

Additionally, cyanobacteria have been investigated for their ability to suppress weed growth. Some species can produce allelopathic compounds that inhibit the germination and growth of certain weed species (Singh *et al.*, 2016 b).

Cyanobacteria play a significant role in soil conditioning and bioremediation due to their unique biological properties. Cyanobacteria have garnered attention for their ability to remediate contaminated soils. As primary producers, they contribute to the improvement of soil structure through the secretion of extracellular polymeric substances (EPS), which help bind soil particles and enhance soil aggregation, water retention, and aeration (Costa *et al.,* 2018; Ali *et al.,* 2024). Cyanobacteria have been studied for their ability to remediate contaminated soils. Human activities, such as urbanization and industrialization, often lead to soil pollution due to chemical contaminants like heavy metals, pesticides, and crude oils. These microorganisms can significantly reduce the levels of pollutants in contaminated sites. When cyanobacteria are applied to treated soils, the accumulation of heavy metals and other pollutants is reported to be lower compared to untreated soils (Sultana *et al.*, 2022). Cyanobacteria can also enhance soil stability. When used as inoculants, they promote the development of biocrusts, which are essential for restoring barren and degraded areas. This biotechnological approach helps combat desertification processes in arid lands by improving soil structure and preventing erosion (Chamizo *et al.*, 2018). Nitrogen-fixing cyanobacteria can be used to improve soil texture, conserve moisture, and scavenge toxic sodium ions from the soil complex. Although information on the genetics of cyanobacterial halotolerance is limited, their application shows promise in addressing salt-affected soils (Nisha *et al.*, 2018). In bioremediation, cyanobacteria demonstrate the ability to sequester heavy metals through biosorption and bioaccumulation, effectively reducing the bioavailability of toxic metals like lead, cadmium, and arsenic in contaminated soils. They also produce enzymes that degrade various organic pollutants, including pesticides and hydrocarbons, thus cleaning up contaminated environments. Moreover, cyanobacteria can help reduce soil salinity by producing exopolysaccharides that bind sodium ions, making the soil more suitable for agriculture. These capabilities make cyanobacteria a valuable tool in sustainable agriculture and environmental management, promoting healthier soils and reducing the impact of pollutants.

Nano-farming techniques involving cyanobacteria

As the scientific community delves deeper into the realm of sustainable farming practices, the integration of cyanobacteria-based techniques, commonly known as “nanofarming”, has emerged as a promising approach to address the growing global demand for food production while mitigating the environmental impact of traditional agricultural methods. Ongoing research will explore the fundamental principles and practical applications of nanofarming techniques involving cyanobacteria, highlighting their potential to revolutionize the way we cultivate and harvest crops. These resilient microorganisms possess extraordinary adaptability, thriving in a remarkable diversity of environments, from nutrient-rich aquatic ecosystems to the most arid, inhospitable landscapes, making them an invaluable resource for innovative agricultural solutions.

Nano-farming is an innovative approach that utilizes nanotechnology to enhance agricultural practices. It includes the application of nanomaterials such as nanofertilizers, nanopesticides, and nanosensors to improve crop production and sustainability (El-Ramady *et al.,* 2023). Cyano-solutions could refer to the use of cyanobacteria, which are beneficial microbes in nano-farming. These microbes can contribute to soil fertility and plant growth, making them a valuable component of sustainable agriculture (Prokisch *et al.*, 2024). The integration of nanotechnology and beneficial microbes like cyanobacteria holds great promise for the future of farming, potentially leading to increased efficiency, reduced environmental impact and better crop yields (Magnabosco *et al.*, 2023).

Cyanobacterial inoculants are a key component in nano-farming techniques, offering a sustainable way to enhance soil fertility and plant growth. Cyanobacterial inoculants are formulations containing one or more strains of cyanobacteria, either in a liquid or solid form, used for inoculating crops or soil (Singh *et al.,* 2011). They can be combined with nanoparticles to improve nutrient delivery, stress tolerance, and disease resistance in plants (Nawaz *et al.,* 2024). These inoculants can be obtained from specialized culture collections or isolated from natural habitats, such as rice fields or soil samples (Venkataraman, 1972). Cyanobacterial inoculants can be applied by coating seeds with a slurry or liquid formulation before sowing (Karthikeyan *et al.,* 2007). Cyanobacteria can be used to promote the development of biocrusts, which are important for combating desertification. They can be inoculated along with nano sand stabilisers to dryland surfaces to increase soil nutrient levels and promote ecological restoration (Lan and Rossi, 2021). In rice cultivation, cyanobacterial inoculants can be applied at the time of transplanting. This is often done in conjunction with mineral nitrogen through urea, applied in splits at various days after transplanting (Shahane *et al.,* 2015). Cyanobacteria can be genetically manipulated to serve as green factories for the production of commodities, enhancing their application in sustainable agriculture (Pathak *et al.,* 2018). The combination of cyanobacterial inoculants with plant growth-promoting rhizobacteria (PGPR) and nitrogen through urea has been shown to increase the concentration and uptake of essential nutrients in crops (Rana *et al.,* 2012; Parewa *et al.,* 2014).

Integrated nutrient management strategies with cyanobacteria

Integrated nutrient management (INM) strategies using cyanobacteria in nano-farming techniques are a sustainable approach to agriculture. Cyanobacteria can interact with plant growth-promoting rhizobacteria (PGPR) to enhance nutrient management and pest control. This synergy can lead to increased crop yields and soil fertility through various mechanisms, such as nutrient cycling and the production of phytohormones and biocidal metabolites (Prasanna *et al.,* 2012). A promising approach in green nanotechnology involves the use of cyanobacteria for the synthesis of nanoparticles, which can be applied in various fields, including agriculture (Hamida *et al.,* 2020). Deploying non-toxic monocultures of cyanobacteria and green algae as biofertilizer inputs can reduce the dependence on chemical fertilizers, thereby enhancing integrated nutrient management systems (Dhar *et al.,* 2015). Integrated nutrient management (INM) practices may involve the use of organic fertilizer alongside inorganic fertilizer, farm waste, crop rotation, cover crops, and conservation agriculture. Cyanobacteria can be part of this integrated approach to maximize crop nutrition and sustainability (Sahu *et al.,* 2023). These strategies highlight the importance of cyanobacteria in sustainable agriculture, offering a holistic approach to nutrient management that benefits both the environment and crop productivity. By integrating cyanobacteria with nanotechnology, farmers can adopt more efficient and eco-friendly farming practices. Cyanobacterial consortia and their synergistic effects in nano-farming techniques in agriculture is an emerging field of study that combines principles from microbiology, nanotechnology and agricultural sciences. This approach aims to leverage the unique properties and capabilities of cyanobacteria to enhance crop productivity and sustainability. Cyanobacterial consortia produce various bioactive compounds, play a significant role in sustainable agriculture, particularly in the context of nano-farming techniques. These consortia, which involve the symbiotic relationship between cyanobacteria and other microorganisms, can enhance crop growth and soil fertility. Nano-farming techniques, which involve the application of nanomaterials and nanostructures in agriculture, have shown promising results in improving crop yields and reducing environmental impacts (Prasad *et al.,* 2017). The integration of cyanobacterial consortia with nano-farming techniques can further enhance the efficiency and sustainability of agricultural practices. The synergistic effects of cyanobacterial consortia in agriculture include increased macro- and micronutrient availability in the soil, enhanced plant growth, and higher crop yields. Additionally, these consortia can serve as biocontrol options for disease-challenged crops and contribute to ecological resilience (Prasanna *et al.,* 2021; Kollmen and Strieth, 2022; Yadav *et al.,* 2017). Nano-farming techniques, which involve the use of nanoparticles to deliver nutrients or protect plants from pests and diseases, can potentially be integrated with cyanobacterial consortia to create more efficient and sustainable agricultural practices conditions. The combination of these technologies holds promise for reducing the reliance on chemical fertilizers and promoting environmental sustainability (Yadav *et al.,* 2017).

Challenges and opportunities of nano-farming techniques in agriculture using cyanobacteria

The integration of nanotechnology with agriculture, commonly known as "nano-farming", has garnered significant attention in recent years due to its vast potential to address various challenges faced by the agricultural sector. One of the promising avenues in nanofarming is the utilization of cyanobacteria to enhance agricultural productivity and sustainability. Nano-farming techniques using cyanobacteria offer a blend of challenges and opportunities in agriculture. The challenges include ensuring responsible and safe utilization of nanoparticles to avoid issues like nanopollution and nanotoxicity in agroecosystems. There is also the need to understand the molecular interactions between nitrogen-fixing cyanobacteria and nanoparticles, which can be complex. On the opportunity side, these techniques can lead to sustainable agricultural practices by improving nutrient delivery, stress tolerance, and disease resistance in crops.

One of the significant challenges is the potential toxicity and environmental impact of nanomaterials used in nano-farming techniques. As the field of nano-farming continues to evolve, one of the significant challenges that researchers and practitioners must grapple with is the potential toxicity and environmental impact of the nanomaterials used in these innovative agricultural techniques. Nanomaterials (NMs) possess unique physical and chemical properties that make them attractive for a wide range of applications, including in the agricultural sector. However, these same properties also raise concerns about their potential to cause harm to the environment and living organisms. The use of nanomaterials in nano-farming techniques such as nano-priming for rapid seed growth, nanofertilizers, nanopesticides, and nanoweedicides has been shown to have numerous benefits, including improved crop yields and accelerated germination processes (Tripathi *et al.,* 2023). Nano-farming approach can potentially enhance soil fertility and crop yields while reducing the need for chemical fertilizers.

Challenges

1. Environmental risks: The introduction of cyanobacteria into agricultural systems poses potential environmental risks. Uncontrolled growth of cyanobacteria could lead to harmful algal blooms, which can produce toxins detrimental to plants, animals, and humans (Paerl and Otten, 2013).
2. Controlled cultivation: Cyanobacteria are highly diverse and can exhibit varying growth rates and metabolic characteristics. Achieving optimal and consistent growth conditions for large-scale cultivation can be challenging.
3. Nutrient requirements: Cyanobacteria have specific nutrient requirements, including nitrogen, phosphorus, and various micronutrients. Ensuring adequate and balanced nutrient supply can be resource-intensive and costly.

4. Environmental sensitivity: Cyanobacteria are sensitive to environmental factors such as temperature, pH, light intensity, and salinity. Maintaining optimal conditions for growth and productivity can be challenging in outdoor settings.
5. Contamination and competition: Open culture systems are susceptible to contamination by other microorganisms, which can outcompete or inhibit the growth of cyanobacteria. Proper sterilization and monitoring are crucial.
6. Harvesting and processing: Efficient harvesting and processing techniques are required to extract valuable compounds or biomass from cyanobacteria cultures, which can be technically challenging and energy-intensive.
7. Regulatory and public acceptance: The application of nanotechnology in agriculture, including the use of cyanobacteria, may face regulatory hurdles and public resistance. Concerns about the safety and ethical implications of using genetically modified or engineered cyanobacteria need to be addressed (Kuzma and VerHage, 2006).
8. Technical challenges: Optimizing the conditions for cyanobacteria growth and ensuring their effective integration into farming practices require advanced technical knowledge and infrastructure. Issues such as the stability of cyanobacteria in different environmental conditions and their interaction with existing soil microbiota need thorough investigation.
9. Economic viability: The initial investment in nano-farming technology and the cost of maintaining cyanobacteria cultures can be high. Farmers, especially in developing countries, may find it challenging to adopt these technologies without adequate financial support and incentives (Rico *et al.,* 2011).

Opportunities

1. Enhanced soil fertility and plant growth: Cyanobacteria can improve soil fertility through nitrogen fixation, which converts atmospheric nitrogen into a form usable by plants. This natural process can reduce the dependence on synthetic nitrogen fertilizers, thereby lowering production costs and environmental pollution (Bano and Iqbal, 2016; Issa *et al.,* 2014).
2. Biofertilizers and soil enrichment: Certain cyanobacteria species can fix atmospheric nitrogen, making them potential biofertilizers for enhancing soil fertility and various growth promoting substances that could reduce reliance on chemical fertilizers and improve soil fertility.
3. Bioactive compounds: Cyanobacteria produce a wide range of bioactive compounds, including pigments, antioxidants, and antimicrobial agents, with potential applications in agriculture, pharmaceuticals, and nutraceuticals.
4. Sustainable crop production: The use of cyanobacteria in nano-farming can promote sustainable agriculture by enhancing soil health and fertility. Cyanobacteria can produce bioactive compounds that stimulate plant growth and protect against pathogens, leading to healthier crops and increased yields (Singh *et al.,* 2016 a). Cyanobacteria-based products

and processes can potentially reduce the reliance on synthetic fertilizers, pesticides, and fossil fuels, promoting more sustainable agricultural practices.

5. Bioremediation: Cyanobacteria have the potential to remediate contaminated soils. They can absorb heavy metals and other pollutants, thereby cleaning up soils and making them suitable for agricultural use (Atigh *et al.,* 2020; Zanganeh *et al.,* 2022).
6. Climate change mitigation: By reducing the need for chemical fertilizers, cyanobacteriabased nano-farming can decrease greenhouse gas emissions associated with fertilizer production and application. Moreover, cyanobacteria can sequester carbon dioxide during photosynthesis, contributing to carbon capture and storage efforts.
7. Carbon sequestration: Cyanobacteria's ability to fix carbon dioxide through photosynthesis could contribute to carbon sequestration efforts and mitigate greenhouse gas emissions in agriculture.

Interdisciplinary collaboration among scientists, engineers, and farmers will be essential to overcome these hurdles and fully exploit the opportunities presented by these remarkable microorganisms. To fully realize the potential of nano-farming techniques using cyanobacteria, extensive research and development efforts are required. Interdisciplinary collaborations among scientists, engineers, farmers, and policymakers will be crucial to address the challenges and leverage the opportunities effectively. Additionally, public education and transparent communication about the benefits and potential risks will be essential for gaining acceptance and fostering responsible implementation.

Emerging trends and potential applications of cyanobacteria in nano-farming

Cyanobacteria are gaining attention for their potential applications in nanotechnology, particularly in the field of nano-farming. The use of genetically engineered cyanobacteria can optimize production and offer unique features not present in their natural form. These engineered strains can be used for nanoparticle synthesis, which is safer and avoids the use of noxious elements. The advancements in this area could revolutionize various fields of research and development, including agriculture. The emerging trends involve the evolution of cyanobacterial strains through genetic engineering and the exploration of recombination approaches to enhance their industrial potential. This could lead to increased commercial avenues for cyanobacteria and address challenges in sustainable agriculture (Govindasamy *et al.,* 2022).

Emerging trends

1. Development of nano-biofertilizers: Recent advances focus on developing nanobiofertilizers using cyanobacteria to enhance nutrient delivery to plants. These biofertilizers encapsulate nutrients at the nanoscale, allowing for more efficient uptake by plants and reducing the need for chemical fertilizers (Kalia and Kaur, 2019; Mahapatra *et al.,* 2022).
2. Genetic engineering for enhanced functions: Genetic modification of cyanobacteria is an emerging trend aimed at enhancing their photosynthetic efficiency and nitrogenfixing

capabilities. Such modifications can lead to higher biomass production and improved efficiency in nutrient cycling, offering substantial benefits for crop yield and soil health.

3. Nanosensors and nanobiosensors: Cyanobacteria can be engineered to produce fluorescent proteins or nanoparticles, enabling their use as nanosensors or nanobiosensors for monitoring environmental conditions, detecting pollutants, or assessing plant health
4. Integration with precision agriculture: Combining cyanobacteria-based nano-farming techniques with precision agriculture technologies is becoming increasingly popular. This integration allows for the precise application of biofertilizers and biostimulants, optimizing resource use and improving crop management practices (Nawas *et al.*, 2024).
5. Sustainable pest management: Research is exploring the use of cyanobacteria-derived compounds for sustainable pest management. These natural compounds can act as biopesticides, reducing the reliance on synthetic chemicals and promoting environmentally friendly agricultural practices.
6. Bioremediation and soil health restoration: Utilizing cyanobacteria for the bioremediation of contaminated soils is a growing trend. Their ability to sequester heavy metals and degrade organic pollutants helps in restoring soil health, making it suitable for agricultural use.

Potential applications

1. Enhanced crop production: Cyanobacteria can be used to produce biofertilizers that improve soil fertility and plant growth. Their ability to fix atmospheric nitrogen and produce growth-promoting substances can significantly boost crop yields.
2. Soil moisture retention: The polysaccharides produced by cyanobacteria can improve soil structure and enhance moisture retention. This application is particularly beneficial in arid and semi-arid regions where water conservation is crucial for agriculture.
3. Carbon sequestration: Cyanobacteria play a role in carbon sequestration, capturing atmospheric CO_2 and converting it into organic matter. This process not only helps mitigate climate change but also enriches soil organic content, enhancing soil fertility.
4. Production of bioplastics: Cyanobacteria can be engineered to produce bioplastics, offering a sustainable alternative to petrochemical-derived plastics. These bioplastics can be used in agricultural applications such as mulching films (plastic films often used to modify soil temperature, prevent moisture growth, limit weed growth and improve crop yield), reducing plastic pollution (Katayama *et al.*, 2018).
5. Bioenergy production: Cyanobacteria can be used for the production of biofuels, providing a renewable energy source for agricultural operations. This application helps reduce the carbon footprint of farming activities and promotes energy sustainability.
6. Phycoremediation of heavy metals: Cyanobacteria have the potential to accumulate and detoxify heavy metals from polluted soils, making them an effective tool for phytoremediation. This capability helps in rehabilitating agricultural lands contaminated with heavy metals.

7. Production of value-added products: Cyanobacteria can be harnessed to produce a range of value-added products such as vitamins, antioxidants, and bioactive compounds. These products can be used in agriculture to enhance crop nutrition and protection.

Conclusion:

Cyanobacteria, nature's tiny powerhouses, offer remarkable potential for sustainable nano-farming techniques in agriculture. Through the integration of cyanobacteria with nanotechnology and innovative farming practices, cyano-solutions provide a promising pathway towards sustainable agriculture. The future of nano-farming lies in harnessing the power of nature's smallest allies for a greener and more sustainable tomorrow. Ongoing research, technological advancements, and collaborative efforts among scientists, policymakers, and stakeholders are crucial to unlocking the full potential of cyano-solutions and driving the transformation towards a sustainable and prosperous agricultural future. Cyanobacteria offer a promising avenue for developing eco-friendly nano-fertilizers, enhancing crop resilience, and improving soil health. The integration of cyano-solutions in nano-farming practices holds the potential to increase agricultural productivity while minimizing environmental impact. However, the responsible adoption of these technologies is paramount to avoid potential risks such as nanopollution and nanotoxicity. Future research and development must focus on optimizing the application of cyano-solutions to ensure they contribute positively to sustainable agriculture and food security. By harnessing the power of microbes, nano-farming can pave the way for a greener, more sustainable future in agriculture.

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ECO-FRIENDLY PACKAGING SOLUTIONS: NANOTECH'S ROLE IN FOOD SAFETY

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Abstract:

A new, exciting, advanced technology which are working on nano scale of particle also used in different fields like food sector, medicinal, biotechnological, agricultural etc. In food sector it is extensively used in the food processing, safety, and packaging. Overall quality of food improved by using nanotechnology including taste, flavour, nutrients bioavailability. In this chapter we describe how nanotechnology work in food packaging including active, smart and improved food packaging. Nanosensors detect the food contamination and sense the environmental stimuli and give potent antimicrobial activity also provide food protection and processing of food. Additionally, also explain how nanoparticles helpful in food packaging.

Overall nanotechnology plays a greater role in food sector.

Keywords: Nanoparticles, Nanoemulsion, Active Packaging, Smart Packaging**,** Improved Packaging

Introduction:

A modern, advanced technology in which nanoparticles are involved known as nanotechnology. These nanoparticles are organic and inorganic in nature. This technology changed the structure of materials at nano scale (1–100 nm) and also produce materials with unique adaptable biological, chemical, and physical properties,

Chellaram *et al.* (2014) and Dera *et al.* (2020). Nanoscale materials provide remarkable advantages to a broad range of scientific and technological fields, such as engineering, materials science, chemical, physical, biological, and medicinal science because of their distinct chemical and physical properties Chaudhry *et al.* (2017). The distinct and important characteristics of materials at the nanoscale is high SA:V ratio Grumezescu *et al.* (2018). As a result, over the past ten years, scientists and researchers from all fields have focused especially on nanotechnology, which is still growing quickly due to its potential uses in energy production, molecular computing, medicinal therapeutics and diagnostics, and structural materials Nile *et al.* (2020). Along with food industry nanotechnology play a vital role in many other fields like medicinal, agricultural etc. In food industry nanotechnology is very important because its crucial role in food protection by detecting the contamination form pathogens, allergens, toxins and also environmental stimuli sense by nano-sensors which are used in smart packaging, Chaudhry *et al.* (2017). Nanotechnology used in different kinds of food packaging very seriously due to makes the food overall fit for cosumption and shelf life of food products also increased by using the nano-active packaging films and coatings Bajpai *et al.* (2018). Microbial and environmental contamination of food also detected by using nano-sensors and, also improve the conditions of food by changing texture, color and flavour of food during the process of food processing Singh *et al.* (2017). Nanoscience involved in food processing has four different components like nanocapsules, nanoparticles, nanoemulsion and nutraceuticals, nanoadditives. Food taste improved by doing the nanoencapsulation of flavour. Emulsion can be defined as heterogenous or biphasic solutions prepared by addition of those liquids that are not dissolved into one another for example oil and water Grumezescu *et al.* (2018). Emulsions can be classified in three different categories based on their size e.g. Macroemulsions (1100□m) also kinetically stable, Microemulsions (200-500 nm) have thermodynamically stable and finally Nanoemulsions (10-100nm) also kinetically stable Aswathanarayan *et al.* (2019). In food industry, lipophilic substances are delivered easily by emulsions and nanoemulsion. Biodegradable coating and packaging films are prepared by active ingredients of nanoemulsion, these coating and films also improved the conditions of food, and then food is fit for consumptions and transportation. Delivery of bioactive compounds easily done with the help of nanotechnology. Nanotechnology mostly used in different kinds of food packaging such as active food packaging, intelligent/smart food packaging and, also in improved food packaging.

Nanosensors are used in smart food packaging to identification of contamination such as environmental, bacterials, pathogens which makes the food toxic or spoilage, toxins. To regulate time, temperature and gases barrier different indicaters are used Kumar *et al.* (2017). So nanosensors play a important role in the protection of food.

Packaging of food products

Packaging of food is a necessary process and integral part of food industry and food sector. For protecting the food from various physical, chemical factors, contamination from pathogens, allergens, and harmful toxins food packaging play a vital role. Nanotechnology used in three different kinds of food packaging shown in figure 1.

Figure 1: Different kinds of food packaging

1. Active packaging

Nanotechnology plays major role in active food packaging. Those nanoparticles which have antimicrobial activities and moisture regulating agents for example oxygen scavengers, CO2 scavengers and emitters includes in active food packaging Yildirim *et al.* (2018). Active packaging systems is essentially required for protection of food and improves the conditions of food and, also extend the good conditions of food products Dias *et al.* (2013). Active packaging system consists of active compounds such as nanoparticles, antimicrobials composites, oxygen scavengers, ethylene absorber, ethanol releaser and Ag- nanoparticles etc. Majid *et al.* (2018). Silver, gold, titanium and their oxide includes in inorganic nanoparticles have been widely used in food packaging Bikiaris *et al.* (2013). Along with metals and metal oxide nanoparticles many other nanomaterials used in food packaging having special properties also discussed in Table 1 (Ashfaq *et al.*, 2022). Metals nanoparticles either direct or indirect contact with components present in the food. Among all the inorganic nanoparticles silver nanoparticles are extensively used metal because of their high potential antimicrobial activity against pathogenic strains Sharma *et al.* (2017). Silver nanoparticles also play a major role in inhibition of the respiratory chain enzymes Damm *et al.* (2008).

Table 1: Nanoparticles used in food packaging (Ashfaq *et al.*, 2022)

Nanomaterials	Polymer matrix	Properties	References
Nanocellulose	Polyvinyl alchol (PVA)/chitosan films reinforced with cellulose nanocrystals	Thermal stability and tensile strength increased. Good antibacterial and antifungal activity.	Perumal *et al.* (2018)
Nanocellulose	Starch-PVA film doped with cellulose nanocrystal	Water absorption, solubility, water vapor permeability (WVP), and strain at break decreased.	Noshirvani *et al.* (2018)
Nanocellulose	Poly (3-hydroxybutyrate) /poly(εcaprolactone) blend films incorporated with cellulose nanocrystals (CNCs).	Blend with 3% weight CNCs showed the best result for mechanical, wettability, optical, and thermal properties.	Garcia-Garcia *et al.* (2018)
Nanostarch	Chitosan film incorporated with βCarotene loaded starch nanocrystals	Solubility, swelling index, and moisture content, and degradation of the film decreased. The radical scavenging activity was 91.5 ± 0.3% for the modified film.	Hari *et al.* (2018)
Nanostarch	Mango kernel films reinforced with cellulose and starch nanocrystals	Modulus, a barrier to water vapor, and TS increased.	Silva *et al.* (2019)

Protein nanoparticles	Whey protein isolate based films incorporated with zein nanoparticles	Water vapor barrier and mechanical properties improved significantly. There was a decrease in the fractional free volume and hydrophobicity.	Oymaci *et al.* (2016)
Chitosan nanoparticles (CNPs)	Hydroxypropyl methylcellulose (HPMC) films reinforced with CNPs	The shelf life of plums and grapes increased.	Shanmuga Priya *et al.* (2014)
Silver nanoparticles (AgNPs)	Starch-PVA film containing AgNPs	Silver-loaded starch-PVA films exhibited antimicrobial activity against *L. innocua* and *E. coli*, *A. niger*, and *Penicillium expansum*. The use of developed films were limited to fat rich food products.	Cano, A *et al.* (2016)
Zinc nanoparticles (ZnO-NPs)	Mahua oil-based polyurethane and chitosan, incorporated with different proportions of ZnO-NPs.	TS, stiffness, antibacterial properties, barrier properties, and hydrophobicity of the film improved. The shelf life of carrot pieces wrapped with the film was extended up to 9 days.	Indumathi *et al.* (2019)
Titanium dioxide nanoparticles (TiO_2-NPs)	TiO_2-containing PVA/xylan composite film	Enhanced mechanical properties, thermal stability, hydrophobicity, and UV shielding performance.	Ren *et al.* (2015)
Titanium dioxide nanoparticles TiO_2-NPs)	TiO_2-NPs applied as ultraviolet radiation blocker in Ecovio®	Light transmission characteristics of the ultraviolet and visible light were modified, the flexibility of film increased, and a new crystalline phase was observed (phase β and phase γ).	Mohr *et al.* (2019)
Nanoclay	Polylactic acid reinforced with nanoclay (bentonite nanoparticle)	Water vapor transmission rate and Global migration reduced, while the biodegradation of the nanocomposites was enlarged due to	Oliver-Ortega *et al.* (2021)
Titanium dioxide nanoparticles (TiO_2-NPs)	TiO_2-containing PVA/xylan composite film	Enhanced mechanical properties, thermal stability, hydrophobicity, and UV shielding performance.	Ren *et al.* (2015)

2. Smart/Intelligent food packaging

Intelligent packaging materials are defined as “materials and articles that monitor the condition of packaged food and also control the surrounding environment of the food” by the European Commission in 2004 Ghaani *et al.* (2016). Many smart devices like barcodes, RFID tags, sensors, and indicators are used in smart food packaging, it is also referred to as intelligent food packaging. These devices are helpful in many ways like communicate, monitor, sense, record, track, and, also indicate information about food safety, quality, and history Kalpana *et al.* (2019). Nano-sensors are the most powerful production of nanotechnology used to check and monitor the external and internal conditions of fresh and processed food products in food industry Caon *et al.* (2017). Since some foods are extremely perishable and destroy when storage circumstances change, a number of indicators, including pH, time-temperature, and leak indicators, used to check the quality of food. Changing the colour of food products detected by freshness indicator by using this indicator the quality of food is known either the food is fit for eating or not. Time and temperature sensors also work regarding the food safety. Thus, the smart food packaging help in prevention of the diseases Zhai *et al.* (2019). Shrimp spoilage was detected by integration of soluble soybean polysaccharide film with curcumin and SiO2 because this film has potential antibacterial activity and also indicates the color changes due to change in pH during shrimp spoilage Salarbashi *et al.* (2021).

3. Improved food packaging

Those nanoparticles which have these properties such as thermal resistance, water vapour and oxygen impermeability, strength, flexibility, biodegradability and UV absorptivity are used in the preparations of improved food packaging materials. As its name implies it is really improve and enhence the mechanical and physical characteristics of food in food industry.The integration of metal oxides with polymers also improves the mechanical, barrier, and light permeability properties Garcia *et al.* (2018). Fish skin gelatin and Ag–Cu nanoparticles based biocomposites have improved mechanical strength, thermal stability, UV barrier properties and antibacterial activity show against gram-positive (*Listeria monocytogens*) and gram-negative (*Salmonella thyphimurium*) bacteria Arfat *et al.* (2017). Nanoclay is also act as the gases barrier and protection provide against UV light. Tsagkaris *et al.* (2018). TiO2 nanoparticles enhance the mechanical and oxygen barrier properties so theses nanoparticles incorporated with starchpectin based films. Increasing the concentration of TiO2 nanoparticle then the UV impermeability of starch-pectin blended films was also increased Dash *et al.* (2019).

Food protection by nanotechnology

Nanotechnology also used to detect the pathogens, toxins in food for safety purpose. In food many pathogens are present like bacteria, viruses, and harmful toxins which makes the food contaminated and poisonous can cause foodborne diseases in human beings. Harmful pathogens such as bacteria, viruses, and toxins in food can be detected by nanoscale sensors and probes with high potential, sensitivity and specificity. Duncan TV (2011). Nanotechnology provide fast and precise information about contamination of food, and thus also useful in prevention of foodborne disease and outbreaks.

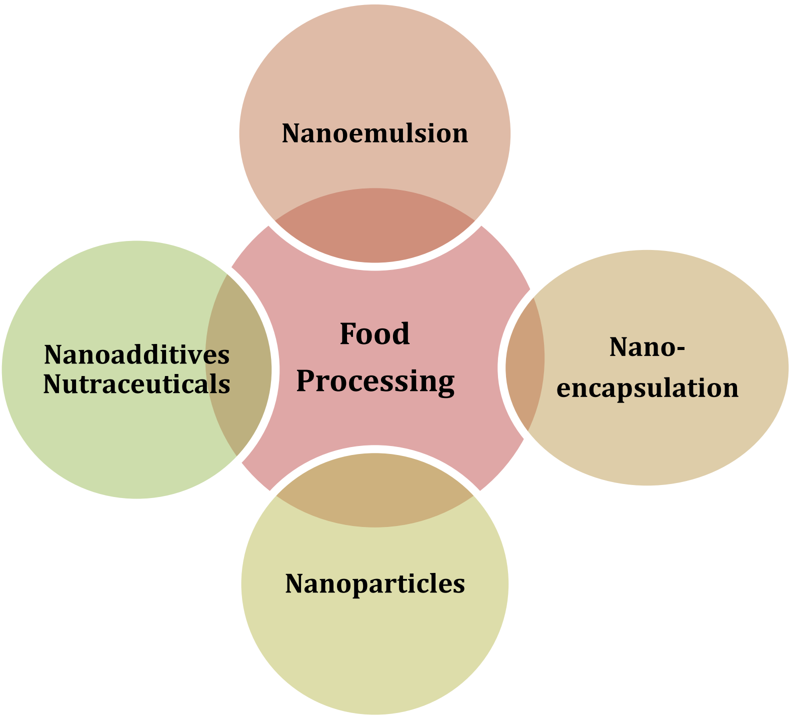

Figure 2: Nanotechnology in Food processing

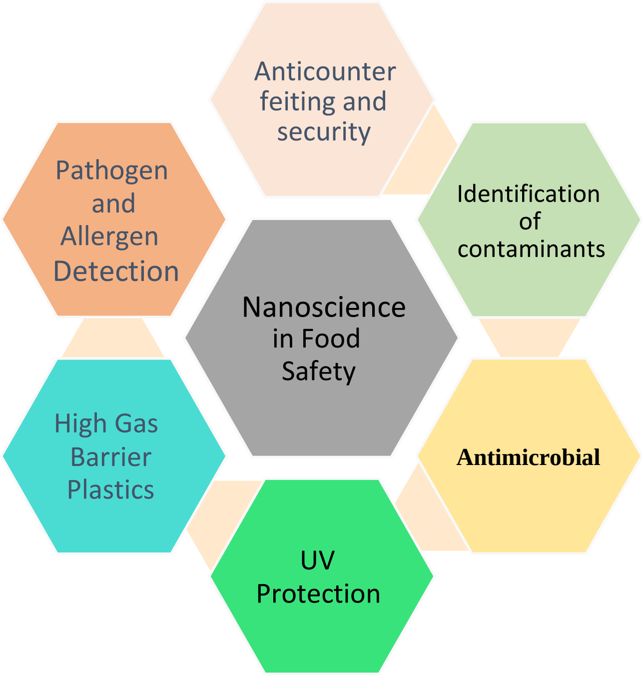

Figure 3: Nanotechnology used in pathogen detection

Conclusion:

Nanotechnology plays a promising and potent role in the food industry. Many pathogens like bacteria, viruses, fungi, and toxins are present in food which makes the food poisonous or toxic for human being. Nano-sensors are used in smart or intelligent food packaging for detecting the environmental, microbial contamination. Mostly organic, inorganic nanoparticles, Nanoclay, metals and metal oxide potentially used in food packaging and coatings. Silver metal is a part of inorganic nanoparticles also give antimicrobial and antibacterial activity due to these, activity extensively used in food packaging films and coatings. This new and exciting technology very useful in every field such as food sector, medicinal, agricultural, and biotechnological.

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NANOTECH-ENABLED GREENHOUSE SYSTEMS: ADVANCING CONTROLLED ENVIRONMENT AGRICULTURE

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Abstract:

Controlled Environment Agriculture (CEA) optimizes plant growing conditions by manipulating temperature, light, nutrient delivery, temperature, and humidity, enhancing quality of crop, crop yield, and consistency. This modern approach includes systems like indoor farms, greenhouses, and vertical farming, enabling year-round production and a reliable food supply. Greenhouses are crucial in CEA for creating optimal conditions, improving resource efficiency and increasing productivity. Technologies like drip irrigation and hydroponics minimize water waste and ensure precise nutrient delivery, significantly reducing resource consumption. Controlled environments also reduce pests and diseases, decreasing the need for chemical pesticides and promoting sustainability. Nanotechnology significantly enhances CEA by improving sustainability, efficiency, and productivity. Key applications include better light utilization through nanomaterials, targeted pest and disease control with nanoparticles, real-time environmental monitoring via nanosensors, and efficient nutrient delivery using nano-fertilizers. These innovations boost crop yields, reduce resource consumption, and minimize environmental impact. However, CEA faces challenges such as high initial investments, technical complexity, regulatory concerns, and public perception issues. Future research will likely focus on developing environmentally friendly nanomaterials and integrating nanotechnology with artificial intelligence and the Internet of Things (IoT) to create more efficient, automated, and sustainable greenhouse systems. Nanotechnology holds transformative potential for CEA, enhancing productivity and resource efficiency. As research progresses, it will play a crucial role in the future of sustainable agriculture, ensuring food security, and meeting global demands.

Keywords: Controlled Environment Agriculture, Nanomaterials, Nanotechnology, Pest Management

Introduction:

Controlled Environment Agriculture (CEA) represents a modern approach to agricultural production where plants are grown within a controlled environment to optimize growth conditions. This methodology integrates advanced technologies to manipulate environmental factors such as light, temperature, humidity, and nutrient delivery, aiming to enhance crop yield, quality, and consistency.

CEA encompasses a variety of systems, including greenhouses, indoor farms, and vertical farming setups. The core principle is to create an optimal environment that maximizes plant growth and minimizes external stressors. This level of control allows for year-round production, irrespective of seasonal variations, thereby offering a reliable food supply.

One of the key benefits of CEA is its potential to significantly increase crop yield. Studies have shown that crops grown under controlled conditions can achieve higher productivity compared to traditional open-field agriculture. For instance, greenhouses can produce yields up to ten times higher per unit area than conventional farming (Despommier, 2010).

The success of CEA largely depends on the integration of various technologies:

1. **Lighting systems:** Artificial lighting, such as LEDs, plays a crucial role in CEA by providing plants with the necessary light spectrum for photosynthesis. Research indicates that LED lighting can improve crop quality and reduce energy consumption compared to traditional lighting systems (Bourget, 2008).
2. **Climate control:** Advanced climate control systems regulate temperature and humidity to ensure optimal growing conditions. These systems often employ sensors and automated control mechanisms to maintain precise environmental parameters.
3. **Hydroponics and aeroponics:** These soilless cultivation methods are commonly used in CEA. Hydroponics involves growing plants in a nutrient-rich water solution, while aeroponics suspends plants in the air and misting the roots with nutrient solutions. Both methods have been shown to use water and nutrients more efficiently than soil-based agriculture (Jones, 2005).
4. **Integrated Pest Management (IPM):** CEA systems often incorporate IPM strategies to minimize pest and disease outbreaks. By using a combination of biological controls, chemical treatments, and cultural practices, CEA can reduce reliance on pesticides and promote a healthier growing environment.

CEA offers numerous advantages over traditional agriculture. These include:

- **Resource efficiency:** CEA systems typically use less water and fertilizer due to the precise delivery of nutrients and water. This efficiency is crucial in addressing global water scarcity issues (Hoestra & Mekonnen, 2012).
- **Reduced environmental impact:** The controlled nature of CEA minimizes the need for chemical inputs, reducing the potential for environmental contamination. Additionally, CEA can be implemented in urban areas, reducing the carbon footprint associated with food transportation.
- **Enhanced food security:** By enabling year-round production, CEA contributes to food security, especially in regions with harsh climates or limited arable land.

Despite these benefits, CEA faces several challenges. High initial capital investment and operational costs can be prohibitive for some farmers. Moreover, the technical complexity of CEA systems requires specialized knowledge and skills, which may limit widespread adoption.

Controlled Environment Agriculture represents a promising solution to many of the challenges faced by traditional agriculture. By leveraging advanced technologies to optimize growing conditions, CEA can enhance crop yield, resource efficiency, and food security. As research and development continue to advance, the adoption of CEA is expected to grow, playing a vital role in the future of sustainable agriculture.

Greenhouse systems are crucial in modern agriculture due to their ability to provide a controlled environment for crop production. By regulating temperature, humidity, light, and CO2 levels, greenhouses create optimal growing conditions, leading to increased crop yield and quality.

Enhanced productivity: Greenhouses allow for year-round cultivation, regardless of external weather conditions, ensuring a consistent supply of fresh produce. Studies have shown that greenhouse-grown crops can yield up to ten times more per unit area compared to traditional farming methods (Despommier, 2010).

Resource efficiency: Greenhouse systems are highly efficient in water and nutrient use. Technologies such as drip irrigation and hydroponics minimize water waste and ensure precise nutrient delivery, significantly reducing resource consumption (Jones, 2005).

Reduced pesticide use: The controlled environment of greenhouses reduces the incidence of pests and diseases, lowering the need for chemical pesticides. Integrated pest management strategies can further enhance pest control while promoting environmental sustainability (Hoestra & Mekonnen, 2012).

Sustainability and urban agriculture: Greenhouses can be integrated into urban landscapes, reducing the carbon footprint associated with transporting food over long distances. This urban integration supports local food systems and contributes to sustainable urban development.

Nanotechnology plays a transformative role in modern agriculture by enhancing efficiency, sustainability, and productivity. The application of nanomaterials offers significant advancements in various agricultural practices.

Precision agriculture: Nanotechnology enables precise monitoring and management of agricultural inputs. Nanosensors can detect soil moisture levels, nutrient deficiencies, and pest infestations in real-time, allowing farmers to optimize water and fertilizer use, thereby reducing waste and improving crop yield (Chen & Yada, 2011).

Pest and disease control: Nanoparticles are used to develop advanced pest and disease control mechanisms. Nanopesticides and nanofungicides offer targeted action with higher efficacy and reduced environmental impact compared to conventional chemical treatments (Khot *et al.*, 2012).

Enhanced fertilizers: Nano-fertilizers provide controlled release of nutrients, ensuring that plants receive essential nutrients over extended periods. This improves nutrient uptake efficiency, reduces leaching into the environment, and enhances plant growth and productivity (Liu & Lal, 2015).

Food safety and packaging: Nanotechnology also contributes to food safety through nanoenabled packaging materials that extend shelf life and detect contamination. These innovations help reduce food waste and ensure safer food supply chains (Silvestre *et al.*, 2011).

Nanotechnology involves the manipulation of matter at the atomic or molecular scale, typically within the range of 1 to 100 nanometers. It encompasses a diverse array of fields, including materials science, chemistry, biology, and engineering, aiming to create novel materials and devices with unique properties and functions (Roco, 2003).

Nanomaterials can be classified based on their dimensions:

- Zero-dimensional (0D): Nanoparticles, quantum dots.
- One-dimensional (1D): Nanotubes, nanowires.
- Two-dimensional (2D): Graphene, nanosheets.
- Three-dimensional (3D): Nanocomposites, nanostructured materials.

Each type exhibits distinct physical and chemical properties due to the high surface area-tovolume ratio and quantum effects (Wang & Xia, 2004).

Synthesis methods:

- **Top-down approaches:** Techniques like lithography and milling reduce bulk materials to nanoscale dimensions.
- **Bottom-up approaches:** Chemical vapor deposition, sol-gel processes, and self-assembly build nanomaterials from atomic or molecular components (Whitesides & Grzybowski, 2002).

Characterization techniques:

- **Microscopy:** Transmission electron microscopy (TEM), scanning electron microscopy (SEM) for structural analysis.
- **Spectroscopy:** X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR) for chemical composition.
- **Surface Analysis:** Atomic force microscopy (AFM) for surface topology and properties (Sanchez *et al.*, 2011).

Nanomaterials for enhanced light utilization: Nanomaterials can improve light utilization in greenhouses by optimizing the spectral properties of light. For instance, quantum dots can convert UV and blue light into red light, which is more efficient for photosynthesis. This spectral modification can enhance plant growth and yield (Pattison *et al.*, 2016). Nanostructured coatings on greenhouse films can also reduce light reflection and increase light transmission, further improving light utilization.

Nanoparticles for pest and disease control: Nanoparticles offer innovative solutions for pest and disease control in greenhouses. Silver nanoparticles (AgNPs) possess strong antimicrobial properties and can be used to control a wide range of plant pathogens (Rai *et al.*, 2012).

Similarly, silica and alumina nanoparticles can act as physical barriers or carriers for pesticides, enhancing their efficacy and reducing the required dosage. This targeted approach minimizes environmental impact and reduces chemical residues on crops.

Nanosensors for environmental monitoring: Nanosensors play a crucial role in real-time monitoring of greenhouse conditions. These sensors can detect various environmental parameters, such as temperature, humidity, soil moisture, and nutrient levels, with high sensitivity and precision. For example, carbon nanotube-based sensors can monitor ethylene levels, a key hormone in plant growth and stress responses (Khan *et al.*, 2017). The data collected by nanosensors enables precise control of the greenhouse environment, optimizing conditions for plant growth and reducing resource waste.

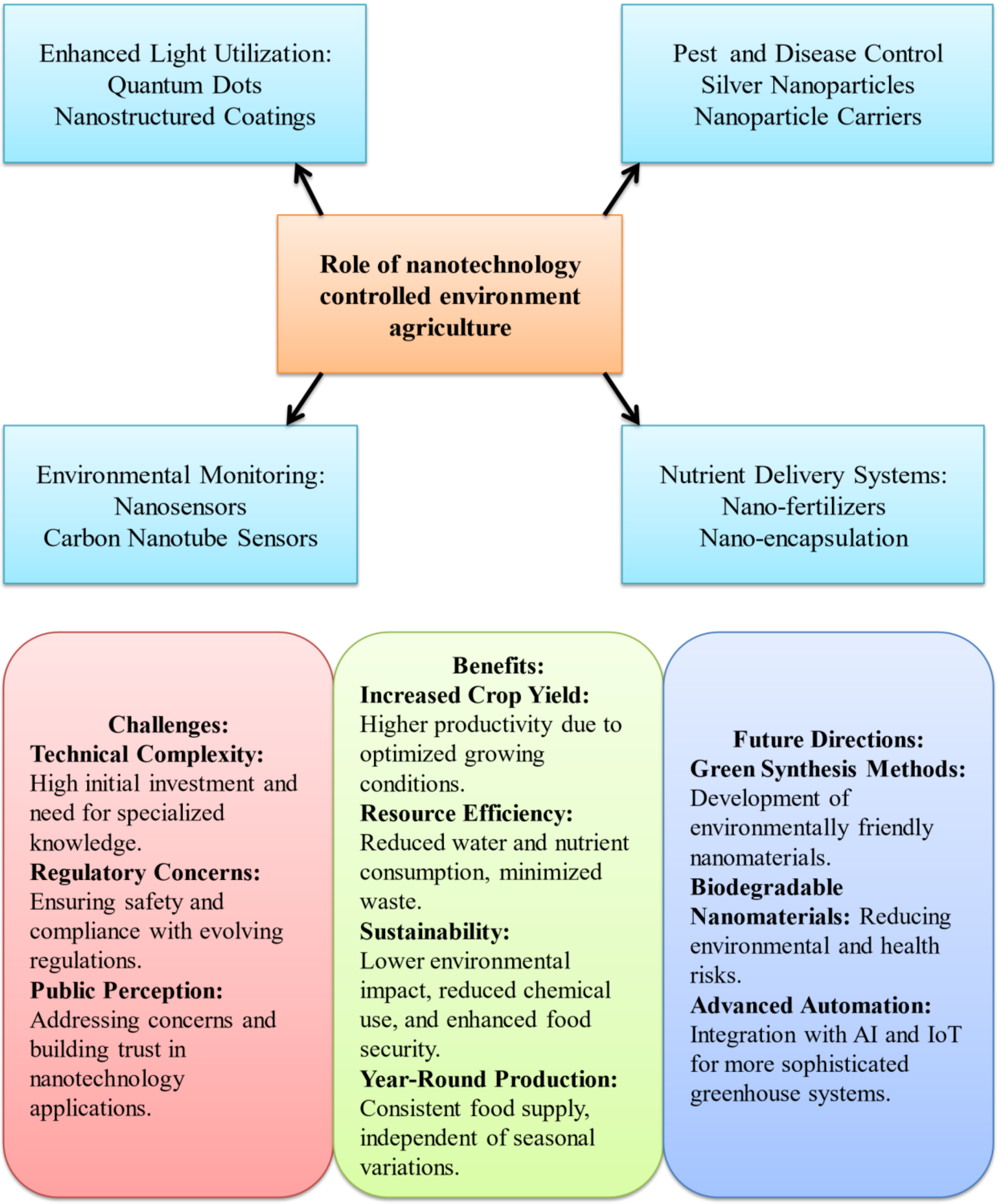
Nanotechnology in nutrient delivery systems: Nano-fertilizers and nano-encapsulated nutrients offer controlled and sustained nutrient release, improving nutrient uptake efficiency and reducing leaching into the environment. For instance, chitosan nanoparticles can encapsulate fertilizers, releasing them gradually and ensuring a steady nutrient supply to plants (Subramanian *et al.*, 2015). This technology enhances plant growth, increases yield, and reduces the environmental impact of traditional fertilization methods.

Technical challenges in implementation: The implementation of nanotechnology in greenhouse systems faces several technical challenges. Developing cost-effective and scalable methods for synthesizing high-quality nanomaterials remains a significant hurdle. Ensuring the stability and uniform distribution of nanoparticles within greenhouse environments is also crucial for consistent performance (Kah & Hofmann, 2014). Additionally, integrating nanotechnology with existing greenhouse infrastructure requires sophisticated control systems and sensor networks, which can be complex and expensive to install and maintain.

Regulatory and safety concerns: Regulatory and safety concerns are critical when introducing nanomaterials into agricultural practices. The potential environmental and health risks associated with the use of nanoparticles necessitate rigorous safety assessments and regulatory frameworks. Current regulations on nanomaterials are often ambiguous and vary between regions, creating uncertainty for producers and consumers (Kuzma & VerHage, 2006). Ensuring that nanomaterials do not pose long-term ecological or health hazards is essential for their sustainable adoption.

Public perception and acceptance: Public perception and acceptance of nanotechnology in agriculture are mixed. While there is recognition of the potential benefits, concerns about the unknown risks associated with nanomaterials persist. Public outreach and education are crucial to address misconceptions and highlight the safety measures in place (Siegrist *et al.*, 2007). Transparency about the benefits and risks, along with clear labeling and regulatory oversight, can help build consumer trust and acceptance.

Future research and development trends: Future research and development in nanotechnology for greenhouse systems will likely focus on improving the efficiency and safety of nanomaterials. Advances in green synthesis methods aim to produce nanomaterials using environmentally friendly processes (Zhang *et al.*, 2013). Research into biodegradable and biocompatible nanomaterials can address environmental and health concerns. Additionally, the integration of nanotechnology with other emerging technologies, such as artificial intelligence and the Internet of Things (IoT), could lead to more sophisticated and automated greenhouse systems, further enhancing productivity and sustainability.



Challenges:
Technical Complexity: High initial investment and need for specialized knowledge.
Regulatory Concerns: Ensuring safety and compliance with evolving regulations.
Public Perception: Addressing concerns and building trust in nanotechnology applications.

Benefits:
Increased Crop Yield: Higher productivity due to optimized growing conditions.
Resource Efficiency: Reduced water and nutrient consumption, minimized waste.
Sustainability: Lower environmental impact, reduced chemical use, and enhanced food security.
Year-Round Production: Consistent food supply, independent of seasonal variations.

Future Directions:
Green Synthesis Methods: Development of environmentally friendly nanomaterials.
Biodegradable Nanomaterials: Reducing environmental and health risks.
Advanced Automation: Integration with AI and IoT for more sophisticated greenhouse systems.

Figure 1: The role of nanotechnology in enhancing greenhouse systems within the framework of controlled environment agriculture, highlighting the key applications, benefits, challenges, and future directions.

Conclusion:

Summary of key points: Nanotechnology offers transformative potential for controlled environment agriculture (CEA), particularly in greenhouse systems. Key applications include enhanced light utilization through nanomaterials, targeted pest and disease control with nanoparticles, precise environmental monitoring via nanosensors, and efficient nutrient delivery using nano-fertilizers. These innovations lead to increased crop yields, reduced resource consumption, and minimized environmental impact.

The future of nanotech in controlled environment agriculture: The future of nanotechnology in CEA looks promising, with ongoing advancements expected to address current challenges and unlock new possibilities. Research is likely to focus on the development of environmentally friendly nanomaterials and their safe integration into agricultural practices. Combining nanotechnology with other emerging technologies like artificial intelligence and the Internet of Things (IoT) can create more efficient, automated, and sustainable greenhouse systems (Rai *et al.,* 2012). The growing market potential, driven by the demand for sustainable agricultural practices, will further accelerate the adoption of nanotech-enabled solutions (Singh and Sengar, 2020).

Final thoughts: Nanotechnology represents a critical innovation in the evolution of controlled environment agriculture. While there are technical, regulatory, and public perception challenges to overcome, the benefits of improved productivity, resource efficiency, and sustainability make it a compelling area of development. As research and technology continue to advance, nanotechnology is poised to play a pivotal role in shaping the future of sustainable agriculture, ensuring food security, and meeting the demands of a growing global population.

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ADDRESSING CLIMATE CHANGE CHALLENGES: NANOTECH SOLUTIONS FOR RESILIENT AGRICULTURE

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Introduction:

Climate change poses significant threats to global agriculture, affecting crop yields, soil health, and water availability. Traditional agricultural practices are often insufficient to cope with these challenges. Nanotechnology offers innovative solutions to enhance agricultural resilience. This chapter explores various aspects of nanotechnology, focusing on its potential to address climate change challenges in agriculture.

The US Environmental Protection Agency defines nanotechnology as the study of comprehending and manipulating matter at dimensions of approximately 1–100 nm, where special physical characteristics enable new uses. This definition is a little tight in terms of measurements of size. It would have been better to emphasize how well the materials could solve problems. Additional definitions of nanoparticles from an agricultural perspective include "particulate between 10 and 1,000 nm in size dimensions that are simultaneously colloidal particulate."(*US Environmental Protection Agency. (2007)).*

Nanotechnology aims at achieving for control of matter what computers did for our control of information. For Drexler, the ultimate goal of nanomachine technology is the production of the "assembler". The assembler is a nanomachine designed to manipulate matter at the atomic level. (Drexler, 1986)

1. Nanotechnology in agriculture: An overview

In nanotechnology, materials are manipulated at the nanoscale (100–200 nm) to produce novel features and capabilities. Nanotechnology can be used in agriculture to create intelligent pesticide and nutrient delivery systems, strengthen soil health, improve water management, and track environmental conditions.

2. Nano-fertilizers and nano-pesticides

2.1 Nano-fertilizers: The regulated release of nutrients by nano-fertilizers improves nutrient uptake efficiency and lessens environmental effects. By optimizing the delivery of particular nutrients to plant roots, these fertilizers can reduce nutrient loss due to volatilization or leaching.

a) **Controlled release**: Nutrients are encapsulated in nanomaterials by nano-fertilizers, which then release the nutrients gradually over time. By ensuring that plants have a consistent supply of nutrients, this promotes better growth and lessens the need for frequent fertilizer applications.

b) **Targeted delivery**: Nutrients can be released exactly where and when they are needed by designing nanoparticles to react to particular environmental factors, such as pH or temperature changes.

c) **Diminished environmental impact**: Through runoff, traditional fertilizers frequently cause water pollution. By increasing nutrient use efficiency and lowering the amount of fertilizer required, nano-fertilizers lower this risk.

2.2 Nano-pesticides: By minimizing off-target effects and enabling focused distribution of active components, nano-pesticides minimize the amount of chemicals required. They can be designed to release insecticides in reaction to particular environmental cues, providing prompt defense against illnesses and pests.

a) **Improved efficacy**: Compared to traditional pesticides, nanoparticles have a greater ability to enter plant tissues and offer superior defense against pests and illnesses.

b) **Lower dosage**: Compared to conventional pesticides, nano-pesticides can accomplish the intended pest control results at lower dosages because of their large surface area and responsiveness.

c) **Environmental safety**: Nano-pesticides lower the danger of environmental contamination and harm to non-target organisms by assuring targeted delivery and reducing the amount of pesticide utilized.

3. Soil health enhancement

3.1 Nanomaterials for soil remediation: Contaminated soils can be cleaned up using nanomaterials like carbon and nano clays. By absorbing heavy metals and other contaminants, these substances enhance the quality of the soil and encourage the growth of healthy plants.

a) **Adsorption properties**: Due to their large surface area and capacity to absorb large amounts of organic and heavy metal pollutants, nanomaterials are effective adsorbers of pollutants.

b) **Enhancement of soil structure**: Specific nanomaterials have the potential to improve soil structure, leading to increased aeration and water infiltration—two essential elements for a robust root system.

c) **Microbial interactions**: Beneficial microbial activity that supports soil health can be fostered by nanomaterials interacting with soil microorganisms.

3.2 Nano-biochar: A type of biochar known as nano-biochar has a higher surface area and reactivity than regular biochar. It can be used to improve soil structure, retain more water, and stimulate microbial activity. By assisting in the sequestration of carbon, its application helps to mitigate climate change.

a) **Carbon sequestration**: Because of its high stability and carbon content, nano-biochar is a useful tool for removing and storing carbon from the atmosphere in soil.

b) **Water retention**: Because of its porous nature, nano-biochar helps soil retain water, which makes it especially useful in regions that are vulnerable to drought.

c) **Enhanced nutrient availability**: By absorbing and releasing nutrients gradually, nanobiochar can increase plant availability to nutrients and lessen the need for chemical fertilizers.

4. Water Management

4.1 Nano-filtration systems: Water may be effectively purified using nano-filtration systems because they eliminate impurities at the nanoscale. With the help of these devices, crops may be properly irrigated, which is important in regions with scarce water supplies.

a) **Removal of contaminants**: Heavy metals, organic pollutants, pathogens, and other contaminants can all be eliminated using nano-filtration membranes.

b) **Energy efficiency**: Nano-filtration systems are frequently more energy-efficient than traditional filtration techniques, which qualifies them for extensive agricultural applications.

c) **Sustainable water use**: Nano-filtration systems help sustainably farmed areas, particularly those where water is scarce, by supplying clean water for irrigation.

4.2 Nano-sensors for water quality monitoring: Real-time detection of contaminants and nutrient levels in water is made possible by nano-sensors, which allow for accurate water management. By reducing water use and avoiding over-irrigation, these sensors assist farmers in optimizing irrigation techniques.

a) **Real-time monitoring**: Farmers are able to react swiftly to variations in the water's quality thanks to the continuous data on water quality that nano-sensors provide.

b) **Precision irrigation**: Water can be applied more accurately based on the real needs of the crops, minimizing water waste, by integrating nano-sensors with irrigation systems.

c) **Pollutant detection**: By detecting pollutants at extremely low quantities, nano-sensors can assist stop the usage of contaminated water that could endanger crops.

5. Environmental monitoring and precision agriculture

5.1 Nano-sensors for soil and crop monitoring: Numerous data, including soil moisture, nutrient levels, and plant health, can be tracked by nano-sensors buried in the ground or affixed to plants. Making knowledgeable judgements about fertilization, irrigation, and pest management is possible with the use of the data gathered.

a) **Evaluation of soil health**: By measuring the pH, nutrient content, and moisture content of soil, nano-sensors can provide comprehensive data on the state of the soil.

b) **Crop health monitoring**: Early intervention is made possible by the ability of nano-sensors to identify signs of plant stress, such as temperature variations or changes in biochemical markers.

c) **Data integration**: Farmers can receive actionable insights for precision agriculture by integrating the data from nano-sensors into digital platforms.

5.2 Drones and autonomous systems: Large agricultural areas can be surveyed by drones fitted with nano-sensors, which can produce precise maps of the soil and crop health. Precision agriculture, which applies inputs only where necessary to minimize waste and environmental damage, is made possible by this information.

a) **Precision application**: Farmers may save input costs and lessen their influence on the environment by utilizing drones to distribute water, insecticides, or fertilizers exactly where they are needed.

b) **Field mapping**: Using precise maps produced by drones, planting, irrigation, and harvesting decisions may be made in a way that maximizes resource utilization and increases yields.

6. Challenges and future prospects

6.1 Regulatory and safety concerns: Safety problems for human health and the environment are raised by the application of nanotechnology in agriculture. It is necessary to create regulatory frameworks to guarantee the secure usage of nanomaterials.

a) **Studies on toxicity**: In-depth research is necessary to comprehend the possible toxicity of nanomaterials to people, animals, and the environment.

b) **Development of laws**: To ensure that the benefits of nanotechnology in agriculture are maximized and the hazards are minimized, clear laws must be put in place.

c) **Public awareness**: Raising awareness among the general public about the advantages and safety of nanotechnology can aid in the adoption and support of these advancements.

6.2 Cost and accessibility: Small-scale farmers may find it difficult to use nanotechnology due to its high development and implementation costs. It is necessary to work on lowering the cost of these technologies and enabling all farmers to use them.

Nanotechnology in agricultural sectors:

Areas of applications	Uses	References
Crop production		
Plant protection products	Nanoparticles encapsulated pesticides, nanocapsules, and nanoemulsions for controlled and on-demand release for better efficiency and disease pest control of plants	Anjali *et al.,* (2012)
Nanofertilizers	Buckyball fertilizer nanoparticles, nanocapsules, and viral capsids for better nutrients absorption of plants and sitespecific nutrient delivery	Anjali *et al.,* (2012)
Precision farming	Nanosensors connected with global positioning system (GPS) navigation system for real-time monitoring of soil environments and crop growth, precise application of fertilizer and pesticide	Kalpana-Sastry *et al.,* (2009)
Soil improvement		
Water/liquid retention	Nanomaterials like zeolites and nanoclays are used to hold water and liquid agrochemicals in soil for their subsequent slow release to products.html plants	http://www. geohumus.com/us/

Water purification		
Water purification and pollutant remediation	Nanomaterials like nZVI nanoclays and carbon nanotubes (CNTs) are used for filtering and binding of toxic substances and their subsequent removal from environments	McMurray *et al.*, (2006)
Diagnostic		
Nanosensors and diagnostic devices	Nanomaterials and nanostructures like electrochemically active CNTs and nanofibers are extremely delicate biochemical sensors used to closely assess environmental conditions, plant status, and growth	Vamvakaki and Chaniotakis (2007)
Livestock and fisheries	Nanoveterinary medicine like nanoparticles, buckyballs, dendrimers, nanocapsules used for drug delivery, nanovaccines; smart herds, cleaning fish ponds	Kalpana-Sastry *et al.*, (2009)
Plant breeding		
Plant genetic modification	Nanoparticles loaded with desired DNA or RNA are delivered to plant cells for their genetic transformation or to trigger defense mechanism activated by pathogens	Torney *et al.*, (2007)
Nanomaterials from plant		
Nanoparticles from plants	Production of nanofibers from bionanocomposite and Nanofibers from cotton waste and wheat straw and soy hulls for improved strength of clothing	Kalpana-Sastry *et al.*, (2009)
Food industry	Use of silicate nanoparticles in airtight packaging of food products and nanosensors for contamination and pathogen determination in food	Kalpana-Sastry *et al.*, (2009)

Advanced nanotechnology concepts for precision farming

Smart dust sensors:

- Developed by University of California robotics scientist Kris Pister, these autonomous wireless small sensors use silicon etching technology for an onboard power source, compute capabilities, detection, and communication with other nearby motes. Currently produced by companies like Crossbow Technologies, Millennial Net, and Ember, with plans from Motorola, Intel, and Philips. Researchers use motes to track the microclimates surrounding redwood trees remotely.

Agrinfortronics:

- Efficient fusion of mechatronics and information and communication technology (ICT) for agriculture. It encompasses sensing, acquisition, analysis, storage, and dissemination of accurate and consistent data about the crop production environment. "Millipede," a data storage concept, combines high data rate, ultrahigh density, and tiny size using scanning probe technology.

Ambient intelligence:

- A new discipline aimed at developing smart environments utilizing artificial intelligence (AI) and sensors to foresee individual needs and react accordingly.

Merits of nanotech solutions for resilient agriculture

Improved control of insects and diseases:

- **Nanopesticides:** Offer focused application, lowering chemical requirements and minimizing environmental impact. Pesticides can be released gradually and under control thanks to nanocarriers, providing long-lasting protection.

Water resources management:

- **Water filtration:** Facilitated by nanotechnology, enhances irrigation water quality by eliminating impurities.
- **Moisture sensors:** Provide precise information on soil moisture levels, aiding in the efficient use of water.

Health of the soil:

- **Remedial soil:** Heavy metal and other polluted soils can be made more wholesome with the use of nanoparticles.
- **Nutrient delivery:** Nanoclays and other nanoparticles can improve soil fertility by increasing nutrient availability.

Management following harvest:

- **Nanocoatings:** Extend the shelf life of fruits and vegetables by protecting them from microbial infections.
- **Nanosensors:** Monitor storage conditions, preventing spoilage and loss.

Demerits of nanotech solutions for resilient agriculture

Hazards to the environment and health:

- **Toxicity:** Plants, beneficial soil microbes, and possibly humans are all susceptible to the harmful effects of nanoparticles.
- **Accumulation:** Long-term ecological effects could result from the accumulation of nanoparticles in the ecosystem.

Financial elements:

- **Cost:** Small-scale farmers may find it difficult to use nanotechnology solutions due to their high production and implementation costs.
- **Market access:** The disparity between large- and small-scale farmers may grow as a result of emerging nations' restricted access to cutting-edge nanotech products.

Safety and regulatory concerns:

- **Lack of standardization:** The application of nanotechnology in agriculture is not governed by extensive laws or standards.
- **Safety:** Little is known about how long-term exposure to nanoparticles will affect the environment and public health.

Technology difficulties:

- **Scalability:** The challenge of expanding nanotech applications for extensive agricultural use.
- **Integration:** Difficulties in incorporating nanotechnology into current agricultural systems and practices.

Conclusion:

Nanotechnology offers promising solutions to address the challenges posed by climate change in agriculture. From enhancing nutrient delivery and soil health to improving water management and environmental monitoring, nanotechnology can transform agricultural practices and promote sustainability. However, careful consideration of safety, cost, and regulatory issues is essential to realize its full potential. As research progresses, nanotechnology is poised to play a critical role in building resilient agricultural systems capable of withstanding the impacts of climate change. The burgeoning applications of nanotechnology in agriculture will continue to rely on the problem-solving ability of the material and are unlikely to adhere strictly to the upper limit of 100 nm. This is because nanotechnology for agricultural applications will have to address the large-scale inherent imperfections and complexities of farm production systems (e.g., extremely low input use efficiency), which might require nanomaterials with flexible dimensions that nevertheless perform tasks efficiently in agricultural production systems. This contrasts with nanomaterials that might work well in well-knit factory-based production systems. Engineered Nanomaterials (ENMs) have the potential to lead the agri-technology revolution by providing advanced sensing capabilities, improving efficiency in nutrient and pesticide delivery, and enabling plants to manage environmental stresses more effectively. Their small size, ability to cross biological barriers, and customizable properties make them an ideal platform for enhancing agricultural productivity and resilience in the face of climate change.

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