Role of Nanotechnology for Precision Agriculture and Food Security

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Abstract

Nanotechnology in precision agriculture provides answers for understanding agriculture's complex difficulties and ensuring food security. Nanotechnology is the use of small-scale materials to improve agricultural practices. Nanotechnology enables farmers to optimize resource utilization such as water and fertilizers resulting in enhanced agricultural productivity. Nano fertilizers provide nutrients to plants more rapidly than conventional fertilizers, resulting in enhanced plant development. Nanotechnology in agriculture is the source of nanopesticides. The nano insecticides compared to traditional pesticides fast action and minimum harm to environment. Nanosensors are a crucial component of precision irrigation system showcasing the significant contribution of nanotechnology in this field. The nanosensors helps farmers to monitor and control water consumption and prevent loss of natural resources. Nanotechnology aids in the precise delivery of water to agriculture. Challenges and ethical considerations must be considered. Nanomaterials may affect humans, animals, natural resources, and the environment. To use them safely, they must be checked. Additionally, everyone must grasp the benefits and risks of nanotechnology in agriculture. Nanotechnology can improve agriculture yields, food security, and environmental sustainability. Nanotechnology and problem-solving can help us create a more secure and efficient food system for everyone.

Keywords: Food security, Food safety, Bio fertilizers, Nanotechnology

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Introduction

To optimize profit, the farming community consistently prioritizes reducing the cost of agricultural inputs. Farmers use fungicides, herbicides, and fertilizers to maximize crop productivity to accomplish this goal (Zhang et al., 2021). The third agricultural revolution, or the well-known "green revolution" of the 1950s and 1960s, has considerably increased agricultural output worldwide and slowed the spread of hunger and malnutrition. Nonetheless, the global population has grown by more than 5 billion since the start of the green revolution. The demographic census has alarmingly projected that by 2050, there will be around 9.60 billion people on earth (Zhang et al., 2021).

Numerous scientific disciplines, including physics, chemistry, pharmaceutical science, material science, medicine, and agriculture, have used nanotechnology. Numerous opportunities in the area of agriculture were made possible by the encouraging outcomes in other domains (Amoatey et al., 2021). The EU Directorate-General for Internal Policies defines precision agriculture as a farming management concept that processes and responds to inter and intra-field crop variations to form a decision support system for whole farm management and maximize output from available resources. Nanotechnology in agriculture has enabled precision farming. Nanotechnology considers nanoparticles under 100 nm (Yadav et al., 2023).

Precision agriculture based on nanotechnology measures crop-based and environmental characteristics using computers, GPS, and remote sensing devices (Sivarethinamohan & Sujatha, 2021). The review looks at how precision agriculture, cloud computing, smartphone-based biosensors, and nanotechnology methods and devices can be used to tag, monitor, and track agricultural products. It also discusses the risks and legal, social, and economic ramifications of nanotechnology in agribusiness.

In addressing concerns of food security, environmental sustainability, and socioeconomic development, the chapter highlights the potential for nanotechnology to increase the productivity and efficiency of agricultural systems (Sahoo et al., 2023). As it plays a useful role we should also consider its drawbacks to the environment. The nano-technological solutions that seek to achieve sustainability in the food processing and agriculture sectors and also an eco-friendly way for sustainability (Khan et al., 2022).

Definition of Nanotechnology

Nanotechnology is a research and technology development at the atomic, molecular, and macromolecular level, helps with controlled manipulation as well study of structures and devices with dimension scales in the 1- to 100-nanometer range (Zehra et al., 2021).

3 Importance of Precision Agriculture

Precision agriculture (PA) is a multidisciplinary concept that uses information technology to increase agricultural output and quality. One of the most important and exciting areas of technology is wireless sensor networks (WSN). We collect, monitor, and analyze agricultural data using this technology. With the help of this interdisciplinary technology, agricultural productivity will rise without sacrificing quality thanks to features like crop strength assessment, insect and disease monitoring, and animal tracking (Kumar & Ilango, 2018). Precision agriculture integrates new technologies like Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing (RS) to help farm producers manage within-field variability to increase the cost-benefit ratio. One of the main contribution of precision agriculture to achieve food security by enhanced and amplified food production (Calicioglu et al., 2019). Food security exists when everyone has physical, social, and economic access to enough safe, nutritious food to meet their dietary needs and live an active and healthy life. Applying this paradigm to agriculture may help us comprehend crop output restrictions and precision agriculture's solutions. This insight may help us develop effective food security solutions for future generations (Zehra et al., 2021).

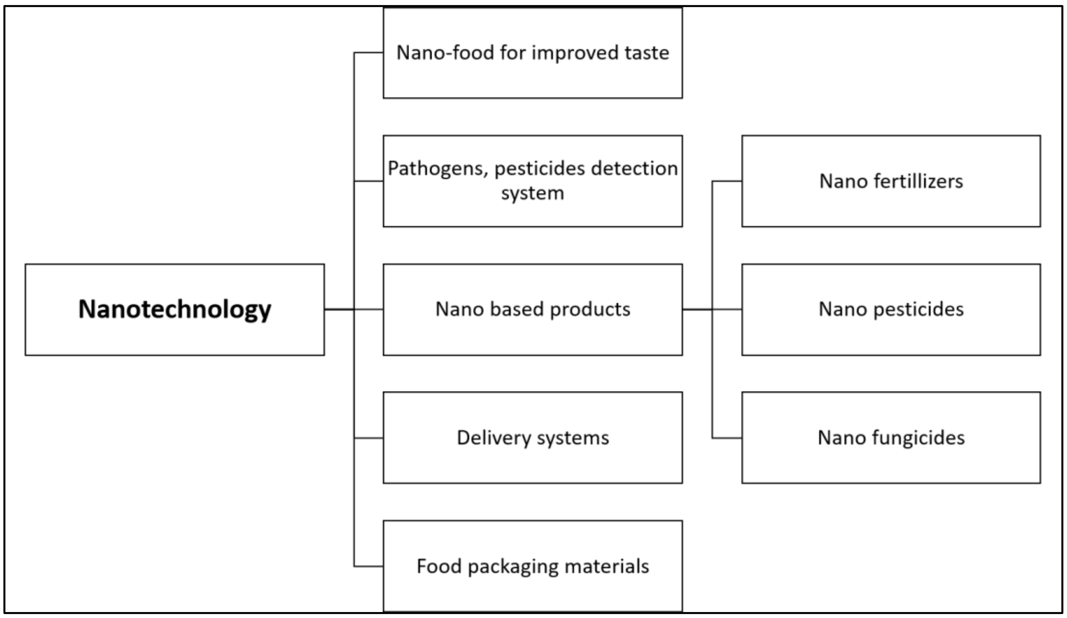

Fig. 1: Nanotechnology for the development of new tastes and textures, delivery of nutrients, pathogen detection or pesticide delivery systems, encapsulation of nutraceuticals and other agents, and food-packaging materials for safety

4 Current Challenges in Agriculture and Food Security

Climate change is affecting the world's weather and water conditions, causing shortages and droughts in some areas and disasters like cyclones and floods in others. The current rate of consumption will worsen the situation. By 2025, water shortages will affect two-thirds of the world's population, increasing the susceptibility of ecosystems (López-Vinent et al., 2020). Climate change will alter numerous agricultural productivity-critical environmental elements. An extensive multi-model assessment of global temperature increases indicated that agricultural droughts increase by 22% in duration and 51% in frequency under a +3°C scenario. Both indexes increased 6.5% and 9.4% from preindustrial values from 1981 to 2010. Runoff rises by 25% but lowers by -20% due to more severe weather events (Seppelt et al., 2022).

Agriculture uses more water than any other industry, yet excessive and careless use leads to significant water loss. The soil is the topmost layer of the ground that is capable of supporting life. One of the largest threats to the environment and human health is soil contamination (Amoatey et al., 2021). Due to water scarcity, treating wastewater may boost soil fertility in dry and semi-arid regions of the world. However, the wastewater effluent can contaminate the soil environment and subsequently, plant metabolism and groundwater quality can be negatively impacted, ultimately affecting human health (Pereira & Cunha Marques, 2020).

Bacterial populations, harvest season, photosynthesis, and harvest respiration will vary with global warming. It converts organic nutrients to inorganic ones and lowers fertilizer efficiency. It also increases soil evapotranspiration, depleting natural resources (Periakaruppan et al., 2023). The circular economy concept seeks to maximize resource allocation efficiency in a semi-closed system to generate more outputs from fewer inputs and maintain growth (Panwar et al., 2021). The issue of food security demands the ability to deal with escalating food shortages for a world population that is constantly expanding. With an estimated 1.7 billion more people on the planet by the year 2050, humanity is placing growing pressure on the finite resources needed to produce our food (Bleeker et al., 2023).

5 Role of Nanotechnology in Addressing Challenges

Nanotechnology can produce foods of exceptional quality in a much more enhanced and practical form, with increased nutritional bioavailability. The increased use of nanotechnology in crop production and food processing is the subject of several research studies (Qureshi et al., 2023). Nanotechnology is one of the most promising fields for increasing food availability and producing new goods with positive impacts on the environment, energy, food, medicine, electronics, and water. With novel and unique uses in agricultural and food research, it is a rapidly emerging and expanding area (Sadeghi et al., 2017). Reducing the amount of pesticides sprayed, minimizing nutrient losses during fertilization, and increasing output via pest and nutrient management are a few areas where nanomaterials in agriculture are emerging. The use of nanotechnology is also playing a role in water conservation (Ulusoy, 2023).

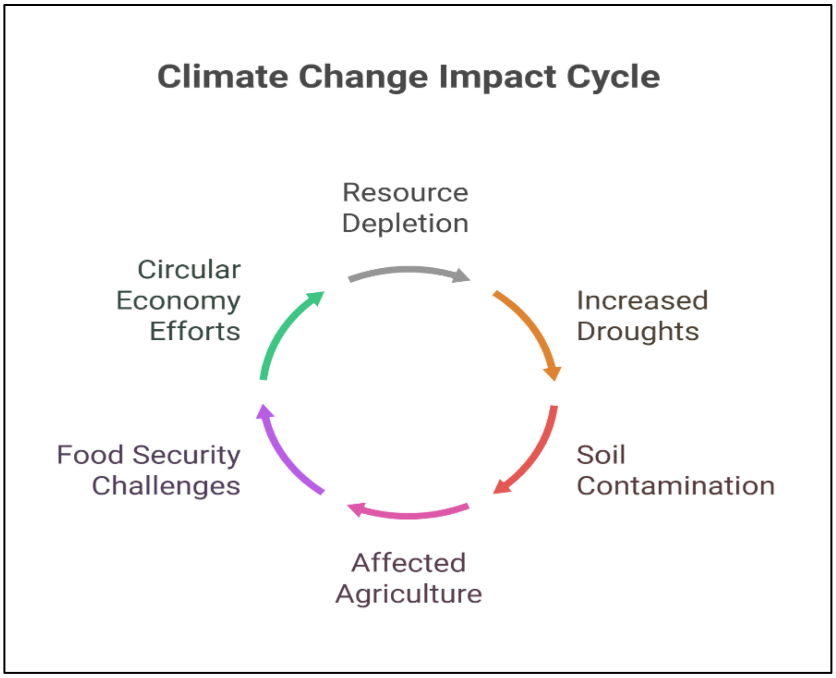

Fig. 2: Impact of climate

6 Fundamentals of Nanotechnology

Nanotechnology refers to the process of creating and manipulating structures, tools, and systems by monitoring their size and shape at the nanometer scale, which ranges from 1 to 100 nm as in figure 3. Just to clarify, a nanometer is equal to one-billionth (10 to 9) of a meter. It suggests that the technology is being used on a very small scale. Nanoscience and nanotechnologies are regarded as creative approaches in developmental study that focus on understanding and manipulating the behavior of matter at the atomic, molecular, or macromolecular levels. At this scale, the characteristics of substances differ significantly from those seen at larger scales (Madkour & Madkour, 2019).

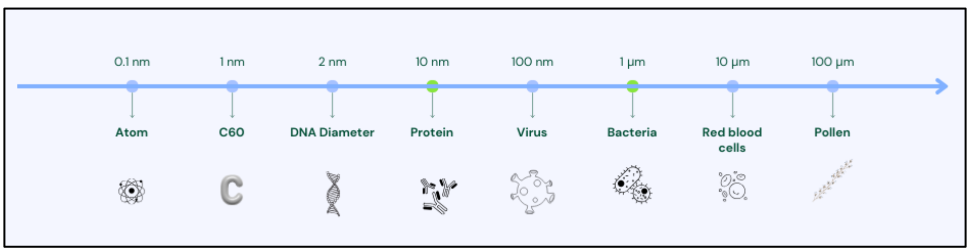

Fig. 3: A pictorial exhibition of things in the "Nano" (<100 nm) and "micro" (>100 nm) size ranges. Where DNA: Deoxyribonucleic acid, C60: Carbon 60.

6.1 Nano-scale Materials and Properties

Nanomaterials are substances that have at least one dimension in the nanoscale range, typically between 1 and 100 nm. Within this size range, the properties of a material tend to differ from its larger-scale counterparts. Nanomaterials can take various forms, including nanoparticles, nanotubes, nano-capsules, nano-spheres, nano-fibers, nano-films, nano-layers, nano-composites, nano-coatings, and nano-sensors (Marcuello et al., 2023). The distinctive characteristics of inorganic nanoparticles frequently arise from their diminutive size, which is less than the mean free path of their electrons (10–100 nm) or the average distance an electron travels before being scattered (scattering length) (Hunyadi Murph et al., 2017). At this particular size, electrons are restricted inside one, two, or three dimensions, and the properties of matter are primarily influenced by quantum mechanical phenomena (Balusamy et al., 2023).

6.2 Nanomaterial in Agriculture

Nanotechnology has shown significant promise in advancing sustainable agriculture. The current advancements in the use of nanotechnology in agriculture mostly focus on enhancing crop productivity and protection as mentioned in figure 5. This involves cleaning up contaminated soils with nano-enabled devices, nano-pesticides, nano-fertilizers, and nano-biosensors. Nanomaterials are essential to many biological and non-biological remediation techniques and play a critical role in determining the fate, mobility, and harmfulness of soil pollutants (Kumar et al., 2023).

6.2.1 Nano Fertilizers

Nano fertilizers improve agricultural. Like vitamins for people, they help plants grow by providing nutrients. Regular fertilizers might waste valuable substances in the air or water. Nano fertilizers keep nutrients where they're needed. They can gently release nutrients, helping plants grow consistently. Nano fertilizers increase crop growth by 18-29%, according to studies. Thus, they may improve farming efficiency and sustainability (Husen & Siddiqi, 2023).

Nano fertilizers aid plants and contain plant nutrients or are nutrients themselves. They ensure crops get what they need for optimal growth without wasting resources. Regular fertilizers may be more expensive and harmful. Nano fertilizers are smart because they store nutrients near plants and release them when needed. Nano fertilizers boost plant health. Recent studies show that nano fertilizers produce crops better than conventional fertilizers, which is great for farmers and the environment (Devi et al., 2023).

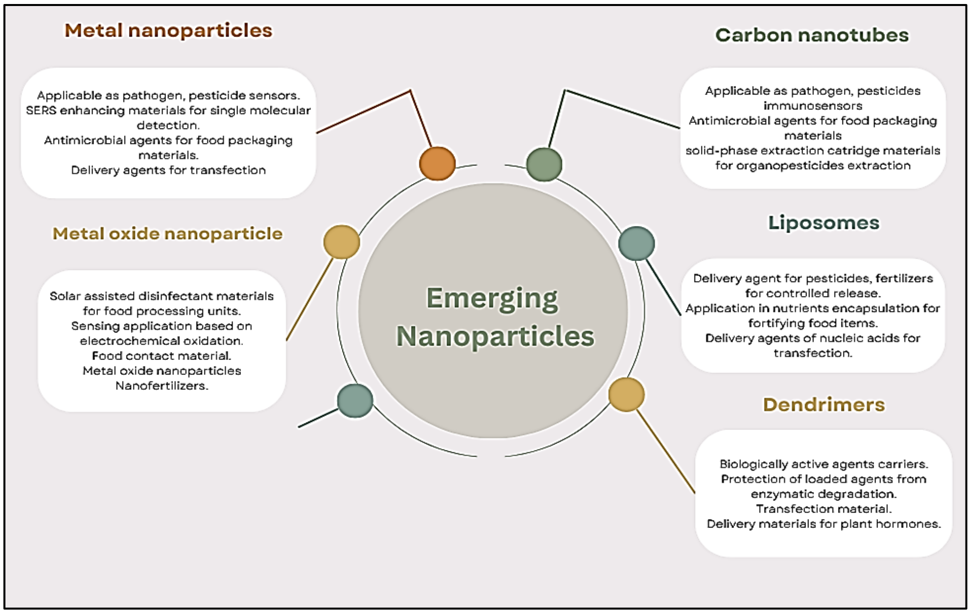

Fig. 4: Major emerging nanomaterials used in agriculture, food, and environment sectors. Graphics of metal nanoparticles, metal oxide nanoparticles, carbon nanotubes, liposomes, and dendrimers are shown along with their potential applications.

6.2.2 Nano Pesticides and Nano Herbicides

Nano pesticides are the solution to overcome the challenges caused due to conventional pesticides in agriculture. Traditional pesticides often cause environmental contamination. These contribute to the development of resistance to pests. It causes risks to humans and the ecosystem (Channab et al., 2024). Nano pesticides provide a targeted and appropriate approach to control pests. In this way it reduced environmental impact, improved efficacy, and improved crop productivity (He et al., 2019).

These Nano-sized preparations act differently from conventional pesticides (Rani et al., 2023). They can decrease the amount and frequency of pesticide application. In this how it is conserving energy and water resources. Additionally, Nano pesticides show better solubility of active ingredients and minimize environmental harm as compared to other chemical pesticides (Yadav et al., 2021).

Nano pesticides against a wide range of pests, including insects, fungi, and weeds. For example, Nano formulations of insecticides like Imidacloprid and permethrin has more efficacy and less environmental impact other than conventional formulations. Similarly, Nano pesticides based on silver, copper, and aluminum shows antimicrobial ability (Xu et al., 2022). Polymeric encapsulated Nano herbicides are far better than conventional herbicides as offer improved efficiency and decrease mobility in soil (Shekhar et al., 2021). The potential health and environmental impacts of Nano pesticides also exist. Nanoparticles can cause hazards to non-target organisms and can kill them. The long-term effects of nanoparticles need thorough evaluation. A detailed risk assessment is necessary to distinguish safe and beneficial forms of Nano pesticides (Dangi & Verma, 2021).

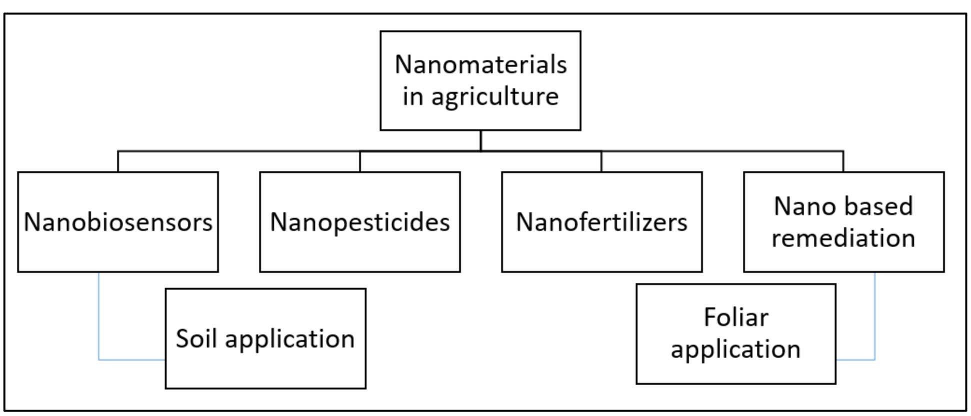

Fig. 5: Nanotechnology's role in agriculture

7 Precision Irrigation

7.1 Evolution of Precision Agriculture (PA)

Precision agriculture (PA) has played a role as a strategic approach to managing variability in farming operations. It has revolutionized agricultural practices since its application in the 1980s (Zurmotai, 2020).

7.2 Integration of GPS and GIS

In the 1980s the advent of the Global Positioning System and Geographic Information System technologies played a significant role (Espig et al., 2020). These technologies have enabled farmers for precise spatial planning and management of agricultural activities (Horstrand et al., 2019).

7.3 Early Applications and Challenges

At beginning applications of PA focused on site-specific operations. Fertilizers application as well as seed selection are the few examples (Espig et al., 2020). The primary obstacles were the limited integration of data and the inadequacy of decision support tools which resulted in decreasing efficacy (Zurmotai, 2020).

7.4 Integration of On-Board Sensor Systems

The integration of onboard sensor systems with computing platforms is used in it. It enabled data collection and modifications to agricultural equipment. In this how many systems are built to improve agriculture against environmental issues (Zurmotai, 2020).

7.5 Enhanced Decision-Making with Biophysical Insights

Precision agriculture solutions use algorithms and biophysical for optimizing agricultural practices. For example variable rate use of fertilizers and spatially variable irrigation management. These are all now based on dereferenced soil sampling and satellite sensor fusion, increasing precision and efficiency (Channab et al., 2024).

7.6 Diverse Stakeholders and Data Sources

Precision agriculture services have a diverse array of stakeholders, from government organizations to private providers and farmer cooperatives (Abioye et al., 2020). Data acquisition sources are public domain to privately held data. Data acquisition requires collaboration and addressing challenges around data standards, sharing them, and ownership (Zurmotai, 2020).

7.7 Nano-scale Water Sensors

Nanosensors are very small platforms designed to get information about measurement and detection at the nanoscale. They can detect biological, chemical, environmental, as well as physical factors. These sensors require the unique characteristics of nanoparticles, such as their surface area-to-volume ratio. This makes them ideal for sensing applications. Nanosensors are used in many areas such as medical diagnostics, food quality sensing, and monitoring water quality having components mentioned in figure 7 (Sadeghi et al., 2024).

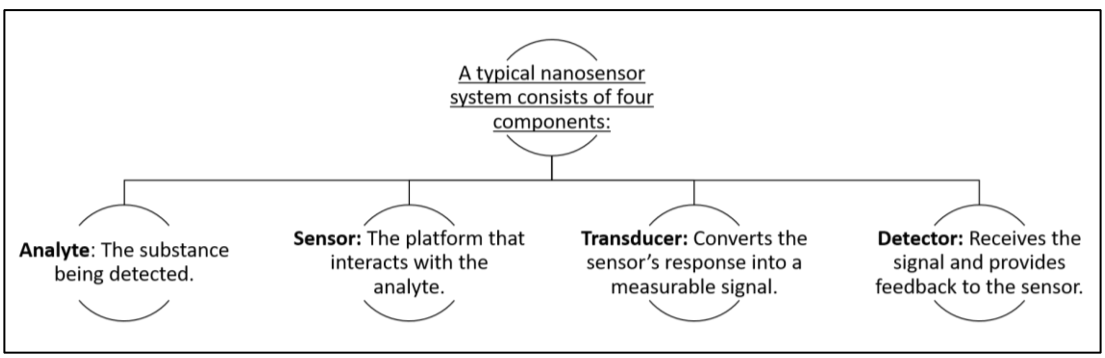

Fig. 6: Components of Nanosensors system

For example, carbon nanotube-based sensors work by detecting changes in conductivity. When specific molecules (e.g., nitrogen dioxide or ammonia) are present, they alter the nanotube's conductivity (Gupte & Pradeep, 2022).

8 Nanotechnology for Food Safety and Preservation

The rapid development of nanotechnology has transformed many domains of food science, especially those that involve the processing, packaging, storage, transportation, functionality, and other safety aspects of food as shown in figure 9.

A wide range of nanostructured materials (NSMs), from inorganic metal, metal oxides, and their nanocomposites to nano-organic materials with bioactive agents, has been applied to the food industry (Ioannou et al., 2020).

8.1 Nanosensors for Food Contaminant Detection

Nanotechnology as a food sensor platform can identify contaminants, notably for food safety and quality applications. Nanomaterial-based chemical and biosensors can be employed online and incorporated into industrial processes and distribution lines as quick, easy, portable, and disposable food contamination sensors (Kuswandi et al., 2017). Pesticide residues, human and veterinary medication residues, microbiological toxins, preservatives, pollutants from food processing and packaging, and other residues can all be found in food.

With their innovative applications, Nanosensors are a new technique that has the potential to identify a wide range of food pollutants, including mycotoxins and several food allergies. The Nanosensors may be combined with wireless technology and utilized online or offline to transmit test findings or contamination warnings in real time to distant servers, enabling quick screening and reporting (Patel et al., 2020).

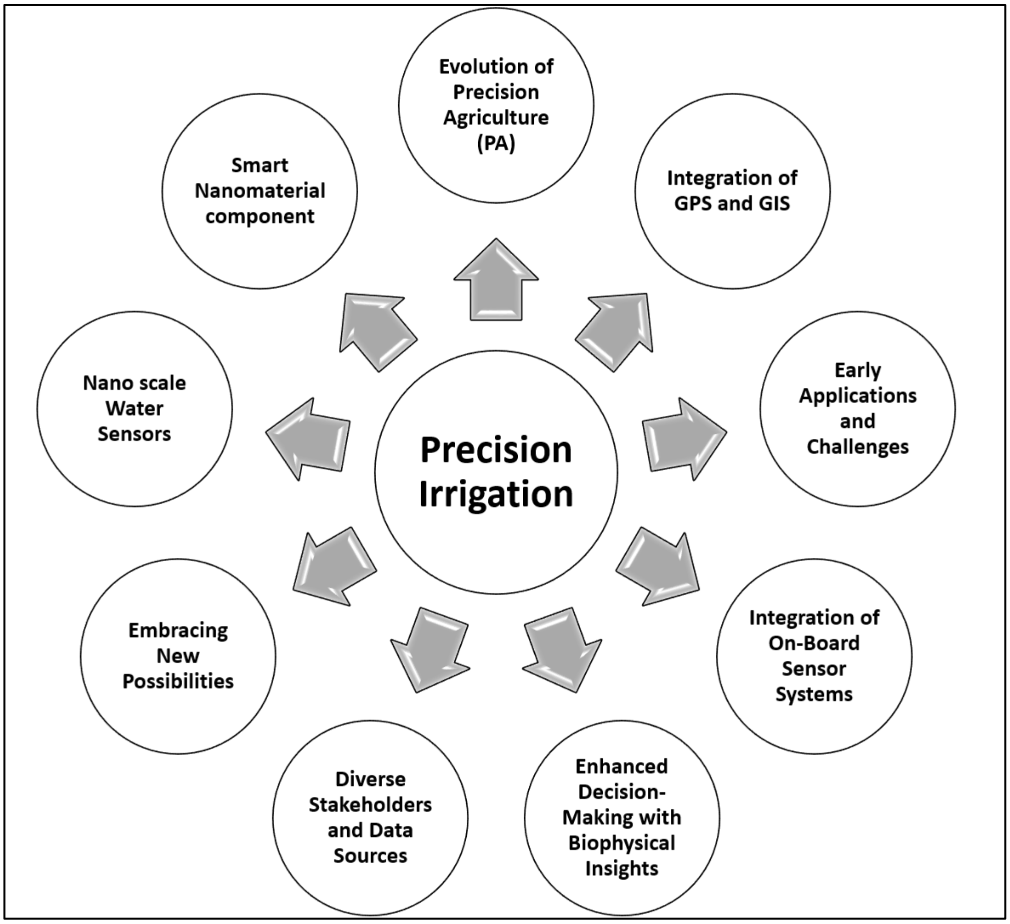

Fig. 7: Precision Irrigation methods

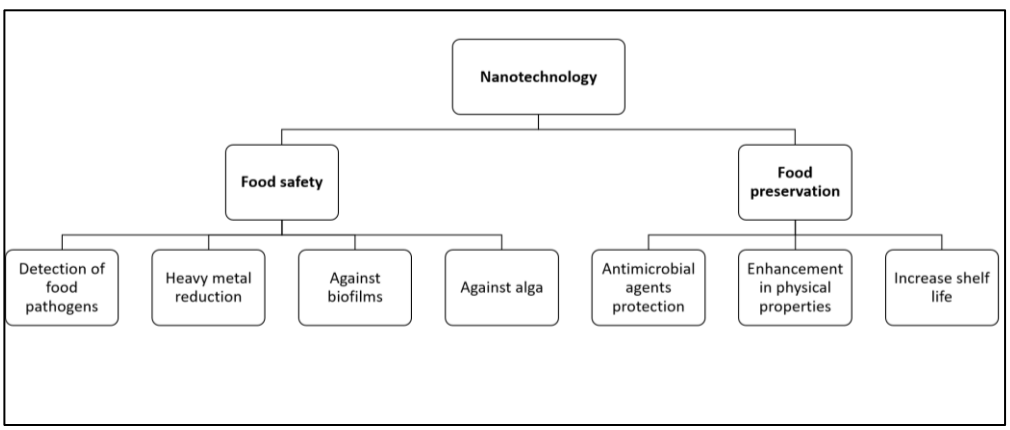

Fig. 8: Nanotechnology role in food safety and food preservation

8.2 Smart Packaging with Nanomaterials

For food preservation and safety following packaging methods are used:

8.2.1 Active Packaging

Active packaging involves the integration of nanomaterials directly into packaging materials to interact with the food contents. These nanomaterials serve various functions such as antimicrobial activity, oxygen scavenging, or UV blocking (Patel et al., 2020). For example, Nano Ag particles show antimicrobial properties. On the other hand, nanoclays increase barrier properties. By nanomaterials packaging actively helps to maintain food quality and safety (Kuswandi & Moradi, 2019).

8.2.2 Smart Sensors

It plays a role in sensing biochemical and microbial changes in food. It facilitates real-time monitoring of food quality. pH sensors also play a crucial role in maintaining food freshness and safety (Kuswandi, 2017). Packaging allows these sensors to provide immediate feedback on food conditions. For example, pH sensors determine acidity levels, while TTIs detect temperature variations. In this how sensors aid in waste reduction and ensure consumer safety (Rai et al., 2019).

8.2.3 Self-Repairing Packaging

Nanomaterials help to develop packaging that can independently repair damage. Nanoparticles containing packaging fill cracks or holes. In this way extending product shelf life and minimizes waste. These self-repairing mechanisms increase packaging lifetime and sustainability. These types of packaging contribute to overall resource efficiency in the food supply chain (Table 1) (Kuswandi & Moradi, 2019).

Table 1: Nanoparticles for application in food packaging.

1	Nanomaterials	Food Item Packed/Uses	Function	References
1	Silver ion and silver NPs	Meats (tuna ham and turkey)	Food contact paper releases silver ions and nanoparticles (NPs), which have antibacterial properties against Gram-negative bacteria in Turkey.	(Rai et al., 2019; Trbojevich et al., 2020)
2.	AgNPs	Chicken meat	There is no silver in chicken meatballs; microbiological testing revealed no distinction between meatballs kept in plastic bags containing silver nanoparticles and those kept in control bags.	(Gallocchio et al., 2016)
3.	Chitosan and ZnO NPs loaded Gallic-acid films	For Active food packaging	Compared to pure chitosan, films exhibit high antioxidant action and a considerable antibacterial capability.	(Yadav et al., 2021)
4.	Nanocrystals from cellulose	Aerogel absorbers for food packaging	A porous and uniform structure with a water absorption capacity.	(de Oliveira et al., 2019)
5.	Graphite carbon nitride Nanosheets	Cherry tomatoes	Films have broad-spectrum antibacterial activity and are safe to use.	(Ni et al., 2021)

8.3 Nanotechnology in Food Preservation

There is a lot of promise for nanotechnology to advance sustainability. It encompasses fields of applied sciences including materials processing, medical, food technology, environmental engineering, physics, and medicine. Materials with one or more dimensions of less than 100 nm are the focus of nanotechnology (He et al., 2019). The technology is being considered increasingly because of its many attributes, which include its wide range of use, target-specific nature, gradual release action, and precise action to active locations (Hamad et al., 2018). Nanotechnology's success may be attributed to its promising outcomes, zero emission of pollutants, energy efficiency, and minimal spatial requirements. In addition to these key success elements, nanotechnology has demonstrated a wide range of applications in the fields of food, agriculture, and the environment with regard to safety, toxicity, and risk assessment (Bhuyan et al., 2019).

9 Environmental and Ethical Considerations

Climate change threatens global food systems with vector-borne illnesses, floods, and livestock and fisheries stress. These issues pose food safety and environmental sustainability hazards. Risk-based food safety reduces consumer hazards but increases greenhouse gas emissions and resource waste (Feliciano et al., 2022).

9.1 Ethical Concerns of Nanotechnology in Agriculture

Scientists and governments must balance the potential advantages of nanotechnology in agriculture with the ethical issues caused by a lack of understanding about its negative effects. Global nanotechnology awareness is low (Bhattacharya et al., 2023). Awareness also differs between low-educated and professionally educated persons. How industry and research approach ethical and social concerns and media presentation in connection to the arguments can impact media representation and public cognition, with general public perception a key factor. Public opinion-focused institutions and scholars shape society most (da Rosa Zavareze et al., 2019).

Nanotechnology in agriculture is complicated by nanomaterials, which can harm humans and the environment, and need product labeling, unclear government financing, and public awareness (Shukla et al., 2024). Like genetic modification issues, there may be strong concerns about public health diseases and cautiousness in introducing the technique. Furthermore, rules are crucial to address these issues and boost technological adoption. Neglecting these concerns will backfire and be remembered like earlier scandals (Srivastava, 2023).

10 Challenges and Future Directions

10.1 Current Limitations of Nanotechnology in Agriculture

We must resolve a few issues and restrictions before extensively using nanotechnology in agriculture (Altabbaa et al., 2023). Lack of detailed rules and procedures to manage nanomaterial usage and eradication in farming are nanotechnology restrictions. Classifying and labeling nanoparticles makes safety and environmental impact evaluation challenging. Nanomaterial toxicity, fate, and transport in plants, water, and soil need further study. Nanotechnology costs more than other resources. Nanotechnology demands trained people, advanced equipment, and cutting-edge methods to develop NMs. Nanotechnology approaches are hard and expensive to transfer from lab to field (Periakaruppan et al., 2023).

Furthermore, farmers' acceptance of nanotechnology may be contingent upon their familiarity with and understanding of NMs. The possible dangers and unknowns associated with nanotechnology for the environment and public health. Nanomaterials could vary from each other by bulk counterparts and it might pose anonymous risks to living things. For instance, nanomaterials can pass through biological membranes. They also engage in interactions to cellular constituents, cause oxidative stress, inflammation, or gen otoxicity. As a result, more research is required to evaluate the instant and long-term impacts of NMs on human health and the environment (Pathak et al., 2024).

10.2 Emerging Trends and Innovations

The Potential of Nanotechnology in Agriculture One potential use of nanoparticles is to help fertilizers and biochemical enter plant systems. Nano carriers, nanocomposites, nanotubes, nanofibers, and nanoclays are crucial (Panda & Das, 2024). Real-time Nano sensor monitoring is ideal for precision farming and future applications. Wireless field sensing systems enable systematic monitoring and real-time data for precision farming. Climate change issues, nanotechnology can boost photosynthesis and plant development. Chemical technology can create sunlight-absorbing chemicals for plants' leaves and roots. Thus, group photosynthesis can be improved and solar energy transformed into chemical energy that plants can store. Though successful, translating sunlight into chemical energy is one of its key drawbacks (Roy & Hossain, 2024).

Conclusion

The integration of nanotechnology into precision agriculture plays a key role for addressing current challenges in agriculture and food security. Nanotechnology offers advance solutions for increasing crop productivity, improve food safety, and optimize resource utilization. Nanotechnology gives efficient nutrient management and pest control. In this way its leading to increased yields also minimize environmental impact. Moreover, Nano sensors play role in precision irrigation, allowing real-time monitoring and optimization of water usage. It is very important associated with the widespread adoption of nanotechnology in agriculture. Climate change and water scarcity create significant challenges to global food systems and nanotechnology offers potential solutions, careful evaluation of its impact on ecosystems and human health is necessary. Ethical concerns regarding public awareness, safety, and regulatory frameworks must also be addressed to ensure responsible and sustainable deployment of nanotechnology in agriculture. Despite current limitations and challenges, emerging trends and innovations in nanotechnology hold promise for the future of agriculture. Nanotechnology has the potential to make advances for farming practices by offering nutrients, by increasing photosynthesis, and enabling real-time monitoring and management of agricultural systems. By carefully using nanotechnology, we can ensure food security, environmental sustainability, and socioeconomic progress for future generations.

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