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Chapter 15

Prospective Trajectories in Nano-Enabled Sustainable Agronomy and Ecological Resilience

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Abstract: Agriculture, essential for providing food, fibre and fuel, has undergone significant transformations due to new technologies, particularly in response to the growing global population. Precision farming increases the crop production with the minimal use of fertilizers and pesticides, helping conserve resources and protect the environment. Nowadays, nanotechnology plays a major role in sustainable agriculture by enhancing efficiency and food security. Smart nano-fertilizers enable controlled nutrient release, reducing waste and soil pollution, while nano-pesticides offer safer alternatives for pest management. The combination of nano-sensors with Internet of Things (IoT) continuously observing the soil and plant health, allowing for factual decisions in resource use. Nano-enhanced irrigation systems and soil restoration methods further improve agricultural sustainability. Additionally, nano-based intelligent packaging helps in extending the shelf life of produce, thus minimizing food waste. However, challenges like regulatory concerns and scalability must be addressed for broader adoption. Overall, nano-enabled sustainable agriculture can significantly enhance productivity and resource efficiency, requiring future research and policies to support safe and scalable implementation.

Keywords: Agriculture, Future trends, Innovations, Nanotechnology, Sustainability.

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1 Introduction

“Zero hunger” which is one of the 17 sustainable development goals of the United Nations is depend upon sustainable agriculture. Rise in global population, environmental pollution, change in climate and increasing energy and water demands are all putting a lot of stress on production and delivery of food. The large quantity of resources is used by modern agriculture is incredible (Usman *et al.,* 2020; Singh *et al.,* 2021). According to the Food and Agriculture Organization, the world's population is predicted to surpass 10 billion by 2050, resulting in a 50% increase in food consumption, especially in developing countries (FAO, 2017). Additionally, 815 million people are thought to be undernourished at the moment, and another two billion are predicted to join this group by 2050. Significant adjustments to the world's food production systems are necessary in light of this circumstance (Kansotia *et al.,* 2024).

Modern farming methods associated with the Green Revolution have significantly increased the global food supply. More sustainable farming practices are required due to their unintended negative impact on the environment and ecosystem services (Singh *et al.,* 2019). The overuse of fertilizers and pesticides has been shown for increasing the number of pollutants and nutrients in groundwater and surface water, leading to water purification and health expenses as well as a reduction in recreational and fishing opportunities. The eutrophication of aquatic ecosystems is a result of agricultural activities that impair soil quality. In order to maintain productivity on deteriorated soils, greater fertilizer, irrigation and energy costs may be required. Other fauna and useful insects are also killed by them. Groundwater levels are dropping in areas where more water is extracted for farming than can be replenished by rainfall. Sixteen percent of the world's crop production takes place on irrigated fields. However, long-term irrigation and drainage practices have accelerated the weathering of soil minerals, increased the acidity of soils, or caused salt buildups, ultimately leading to the abandonment of some of the best agricultural lands. The carbon profile in soils has also been more severely more damaged by heavy irrigation, tillage, and fertilizer application than by traditional farming practices (Mukhopadhyay, 2014). Recent studies have demonstrated that nanotechnology has the potential to enhance the agricultural sector by increasing the effectiveness of agricultural inputs and providing remedies to agricultural and environmental issues to increase food security and productivity. Numerous nano-enabled applications, production techniques and engineered nanomaterials are being tailored to the agricultural sector. Nanotechnology takes advantage of the fact that materials at the nanoscale frequently exhibit distinct physicochemical and biological characteristics that are significantly differ from their mass counterparts. New structures, tools, and systems can be created to accomplish unique tasks that are challenging to accomplish with traditional methods by modifying matter at the nanoscale (Kansotia *et al.,* 2024).

Nanotechnology is focused research and development aimed at understanding, manipulating and measuring materials with atomic, molecular and supermolecule dimensions. The term "nanotechnology" refers to methods, materials and procedures that function at a size of 100 nm or less. In general, the word “nano” describes 1 to 100 nm size. Comparatively speaking, visible light has a wavelength of 400-700 nm. Leukocytes are 10,000 nm in size, bacteria are 1000-10,000 nm, viruses are 75-100 nm, proteins are 5-50 nm and deoxyribonucleic acid is around 2 nm wide, while an atom is about 0.1 nm. At this size, materials’ physical, biological, and chemical characteristics vary widely from one another and can display unexpected behaviours. Nanotechnology takes into account the magnitude of viruses and other diseases. Therefore, it has a significant potential for pathogen identification and elimination. Nanotechnology-driven developments could fundamentally alter farm-to-fork agricultural systems. While increasing the efficiency of input utilization, smart nano-formulations can improve crop growth, yields and nutritional quality. Real-time tracking of crop, soil and animal health indices is made possible by sophisticated nano-sensors and nanoparticle tags. More efficient crop protection and fortification is made possible by precision nanoencapsulation, controlled release and targeted delivery. Increased agricultural reuse of drained water, municipal wastewater and industrial effluents is supported by water-saving nanomembrane filtration systems. Novel approaches to waste management, greenhouse gas emission reduction and agricultural contamination are provided by nano-catalysts and nano-engineered processes (Mousavi and Rezaei, 2011).

With a focus on the most recent developments in precision farming, smart delivery systems and nanomaterials, this chapter examines the trends and breakthroughs that will shape nano-enabled sustainable agriculture in the future. Furthermore, the combination of data-driven decision-making, artificial intelligence and nanotechnology is expected to revolutionize agricultural efficiency and sustainability. By examining cutting-edge research, potential challenges and real-world applications, this chapter provides insights into how nanotechnology is being made possible for a more resilient and renewable global food system. Nano-enabled sustainable farming represents the next phase of advancements in agriculture, offers accurate, economical, and ecologically friendly solutions. With ongoing advancements in research and development, nanotechnology will be key to solve worldwide food security issues and ensuring sustainability of agriculture.

2 Key Innovations in Nano-enabled Sustainable Farming

Nano-enabled sustainable farming is driving a turning point of smart, effective and environment feasible agriculture. From precision nano fertilizers and biodegradable pesticides to AI-driven nano-sensors and climate-resilient crops, these innovations offer practical solutions for improving food security and reducing environmental impact.

2.1 Nano Fertilizer

Nano fertilizer provides certain nutrient-based nanoparticles, which improves growth and development of plant. Further, it offers excellent fertilization effectiveness, sustainable plant nutrient sources and the right nutrients to support soil applications and overall growth of plant (El-Saadony *et al.*, 2021). On the basis of plants' nutrient requirements, nano fertilizer can be classified into three types of fertilizers *i.e.*, macro, micro and nanoparticulate. NPs are coated with macronutrient nano formulations, such as nitrogen, phosphorus, potassium, calcium and magnesium, give plants the right quantity of fertilizer when they need it (Basavegowda & Baek, 2021).

NPs' high volume-to-surface ratio lowers the amount and efficiency of macro nano fertilizer as compared to conventional fertilizer. For optimal plant growth, numerous scientists have created macro-nano fertilizers. Micronutrients which are in the nanoform include vitamins C and B along with many minerals like magnesium, boron, copper, iron, silicon and zinc boost plant biomass and nutrient bioavailability. Improved solubility, increased nutrient uptake and controlled nutrient release are all benefits of the agricultural revolution brought about by nano fertilizers. Because they are less harmful to the soil, reduce nutrient loss and make precise nutrient requirements available, nano fertilizers outperform conventional fertilizers, demonstrating their revolutionary influence on contemporary agriculture (Khatri & Bhateria 2023).

2.2 Nanotechnology for Abiotic and Biotic Stress Resilience

Nanomaterials employ a variety of techniques to safeguard plants; however, they are challenged by a number of environmental stressors. Abiotic and biotic stressors both lead to decreased plant growth, yields, shelf life and product quality, which eventually results in financial losses. Adding helpful bacteria, fungus and insects to seeds can counteract these effects and promote plant growth.

Additionally, the long-term plant protection effects of agrochemicals- a group of insecticides, pesticides, bactericides and fungicides- can minimize chemicals use chemicals on plants. Those chemicals showed improved yield, ecological balance and reduced ecotoxicity (Gahukar & Das, 2020). Furthermore, NPs can boost secondary metabolism in plants, enhancing their resistance against biotic and abiotic stresses (Garcia-Ovando *et al.,* 2022). But how plants respond to these techniques relies on a lot of factors, such as the type of NP utilized, the type of plant, and the growth and development of the plant.

2.3 Nano Pesticide

Only a small percentage of more than 4,00,000 tons of pesticides used in crops each year-between 1 to 25 percent- make it to the target species, posing a possible environmental risk (Zhang, 2018). Additionally, inadequate pest and disease control accounts for 20–40% of crop losses, reducing the agricultural industry by nearly US$220 billion annually (FAO, 2019). To control prevalent pests in agricultural areas, traditional agriculture techniques have led to increased insect resistance, disturbed soil biodiversity, and environmental pesticide bioaccumulation. The best active chemicals can be delivered precisely with nanocarriers, sometimes referred to as smart delivery systems, to allay these environmental worries (Zhao *et al.,* 2017).

Achieving optimal nano pesticide adhesion and deposition on the leaf surface is crucial for increasing the effectiveness of nano pesticide use and reducing losses (Yu *et al.,* 2017). By using foliar and soil application, respectively, Plant tissues may be penetrated by the NPs via the root or the shoot (Ali *et al.,* 2021). Because of their large surface area and elevated surface reactivity, the NPs can deposit on the epidermis of plants by hydrophobic affinity, adhesion, and electrostatic adsorption (Achari & Kowshik, 2018). For instance, nano bactericides with a size of 14-32 nm may be rapidly absorbed by the tomato's phloem and mesophyll tissues by their deposition on the epidermis and cuticle (Zhang *et al.,* 2020). The hydathodes in weeds allow the 256-345 nm sized nano pesticides to directly enter vascular tissues and mesophyll, whereas biological barriers allow smaller nanoparticles to reach cells because of size-limited structures (5-20 nm) (Bombo *et al.,* 2019). Cells can still be penetrated by large nanoparticles of 80-200 nm due to interactions with the cell wall, such as, pore formation, carrier proteins, endocytosis, or cracks at lateral roots (Li *et al.,* 2020).

2.4 Nano and Micro scale Encapsulation

The technique which involves covering the object or embedding it in a heterogeneous or homogeneous matrix for producing the capsules with a variety of beneficial qualities is called encapsulation (Rodriguez *et al.,* 2016). These techniques are beneficial for precision targeting, controlled release and shielding materials or objects from unfavourable conditions (Ozdemir and Kemerli, 2016; Ezhilarasi *et al.,* 2012). Different encapsulation technologies are stated on the basis of the capsules' shape and size. For example, (macro) encapsulation/coating produces capsules in the macroscale, while particles in the micro- and nanoscale size range are produced via micro- and nanoencapsulation. Drug delivery, food fortification, the preservation and improvement of food ingredients or nutraceuticals' bioavailability, the self-healing of different materials, and the vast potential phenomena in plant science have all attracted a lot of attention recently (Ozdemir & Kemerli, 2016).

2.5 Nano Sensors

Numerous benefits of nanoscale materials' physical-chemical characteristics can also be used in the development of biosensors. According to Sagadevan & Periasamy (2014), novel signal transduction technologies utilizing nanomaterials can improve biosensor performance and sensitivity. Rapid, sensitive and affordable nano biosensor systems are highly sought after in critical human activities like food and drink production, agriculture, health care, environmental monitoring, genome analysis, defence and security. This has led to a tremendous advancement in nano biosensor technology. The development of biosensors based on nanotechnology is still in its infancy (Fogel & Limson, 2016).

Sensors are the result of the advancement of instruments and processes for creating, measuring and imaging nanoscale objects. The applications of nanomaterials including carbon nanotubes, magnetic nanoparticles, nanoparticles, metal (gold, silver, cobalt, etc.) and quantum dots (QDs) in biosensors- a new multidisciplinary frontier between material science and biological detection- have been thoroughly studied. Thus, a biosensor is a device that incorporates a biological recognition component with chemical or physical principles. It combines an electronic and biological component to produce a quantifiable signal component. The transducer process is used for biological recognition and electronic achievement is used for signal processing.

2.6 Nanotechnologies in Food Industry

Nanoscale biosensors can be used in the diagnosis and detection of pathogens. Nanotechnology can advance our understanding of food materials at the nanoscale while providing bioactive elements in foods to hosts (Martirosyan & Schneider, 2014). Additionally, it aids in nanoscale filtration systems for better food texture adjustment. Food's glaziers and colours are preserved by nano biosensors' interaction with its appealing surface and magnetic nanocomposite for tag sensors. controlled release, intelligent packaging, nano printing, nano-additives and nano coding of paper and polymers for identification and authentication. Aspects including label and packaging sensing, in situ sensors, food quality monitoring (colour, taste, texture, etc.), control and delivery of nutraceuticals, portable DNA/protein chips, etc., should all be covered in food quality tests (Siegrist *et al.*, 2008).

In the food industry, companies must package and label their products to maintain critical elements like quality, safety, freshness, taste, etc. throughout the supply chain. For researchers and manufacturers, creating intelligent packages that can offer helpful information remains a significant problem. The food business has recently produced and employed some packaging materials that are integrated with “nano sensors” to identify the oxidation process in food. The operation is rather straightforward: NP-based sensors detect a colour shift when oxidation takes place in the food packaging, allowing for the observation of information about the type of food being packed. According to Bumbudsanpharoke & Ko (2015), this method has been effectively used in milk and meat packaging. NPs can be used in food packaging because of their nanostructure, which makes them effective barriers for diffusion gasses like carbon dioxide and oxygen. Because of the reduced weight of packaging materials, longer shelf life and reduced CO_2 loss, some beverages (beer, soda waters, etc.) that must naturally retain a certain quantity of carbon dioxide can be packaged in bottles constructed of nanocomposites. Another way to take advantage of nanoparticles is by using them in packaging; this technique slows down biological processes like oxidation and breakdown, extending the shelf-life of food goods. The most often materials in the industry of food packaging are plastic polymers, which can be coated or integrated with nanoparticles to enhance their mechanical or functional qualities (Berekaa, 2015).

Additionally, nano coatings have antibacterial or barrier qualities on surfaces that come into touch with food. Silver nanoparticles have been effectively incorporated into plastic to create food storage containers, which serves as a disinfectant and reduces the growth of dangerous bacteria. According to Bumbudsanpharoke & Ko (2015), nanotechnology is a forward-thinking method that serves as agricultural biosecurity. When paired with reactive nanolayers or NP-based intelligent inks, nano sensors can help with food labelling and perhaps offer intelligent food product recognition. The food package’s printed labels can highlight important details like time, pathogens, temperature, humidity, freshness, etc. Nano barcode materials having gold designs that can form templates and also have silver stripes that can synthesize themselves.

2.7 Precise genome editing enabled by Nanotechnology

The development of sustainable farming methods and new opportunities for crop improvement have been made possible by the introduction of precise and efficient plant genome editing technologies (Li et al. 2021; Rahman *et al.,* 2022). CRISPR/Cas (CRISPR-associated protein), one of the most popular technologies, has transformed crop genome editing by enabling precise genome alteration that produces high-yielding and stress-tolerant crop types (Sharma & Lew, 2022). The food and cattle industries have widely adopted the CRISPR/Cas9 system in combination with nanotechnology (Islam *et* *al.,* 2020). The genome editing method gains a degree of accuracy from the species-specific NPs. However, further advancements in specialized nanotechnological instruments are needed to fully investigate the potential of genome editing systems controlled by CRISPR in plant biology. Nanomaterials enable organelle-specific CRISPR/Cas genome changes, which have been used to detect infectious diseases and lower infection rates (Zafar *et al.,* 2020).

2.8 Precision Farming

Conventional farming methods have led to serious environmental problems, including the release of greenhouse gases, because they rely too much on agricultural inputs including water, chemicals, equipment and others. Aiming to protect the environment and increase crop productivity, precision farming, commonly referred to as smart farming, has emerged as a solution to this problem. Food safety, sustainability, crop quality, productivity, profitability and economic development could all be greatly improved by precision farming. It is revolutionizing agriculture globally. A crucial element in achieving these objectives is precision farming (Zhang *et al.,* 2021). Precision farming has become even more crucial as a result of the sharp rise in the price of raw resources like synthetic fertilizers and insecticides due to the restricted supply of petroleum and natural gas (Majumdar & Keller, 2021). However, some farmers may find it difficult to adopt precision farming. The complex procedures, including computerized condition of field assessment and data that follows, which are essential elements of smart agriculture, may be too much for some people to handle or accept (Klerkx *et al.,* 2019).

The goal of precision agriculture is to gather as much real-time data as possible by using computers, sensors, remote-sensing equipment and GPS systems (Duhan *et al.,* 2017). Nano sensors are a great method to take precision farming to the next level. Under such circumstances, contaminations and diseases that impede crop growth and lower agricultural yields are promptly detected by nano sensors. Nano-based light-emitting diodes integrated into electronic devices are used to measure the amount of chlorophyll in plants, which drastically lowers the use of pesticides and other agrochemicals. Using enzyme inhibition or nano genetics, a number of nano biosensors may identify and quantify various micro-organisms for precision farming. In order to constant evaluation and traceability of elements that contribute to output enhancement, these offer the prudent and sustainable use of chemicals and resources. Another advantage is that nano biosensors can perform better in complicated matrices, like soil that has accumulated chemicals and less homogenized which makes background noise.

Precision farming is anticipated to create agricultural robots with nano biosensors in the near future, that could act as a “decision support system” for the farmers by specifically helping in weeding (Acharya & Pal, 2020). Under stressful circumstances, these biosensors are in charge of "sensing, monitoring and detection" of any biochemical or biophysical signal at the molecular or cellular level. This industry necessitates ongoing research and innovation to be able to fully appreciate the possible benefits for the sustainable environment and world food security (Chand Mali *et al.*, 2020).

2.9 AI driven Nanotechnology

The process of artificial intelligence has taken up a significant amount of space in people's daily lives. According to Sacha et al. (2013), this technology has numerous fundamental uses that may be used to different industries and enterprises. Everything on Earth is composed of atoms. By observing, accessing and using these atoms, nanotechnology has made it easier. At an unimaginable speed, AI must analyse and compile the collected data from that location into a useable format. For more than the past ten years of research, studies have shown a significant rise in AI in nanobiotechnology. These days, one of the biggest problems scientists' faces is the recreation of data from a nanoscale experiment. When using a microscope for a nano scientific application, for example, the images taken at the nanoscale measurements must be interpreted, which becomes a challenging task. This is where AI enters the picture, converting, interpreting and recreating the data at a level that can then be used for a variety of purposes at a higher quality (Zohuri *et al.*, 2017).

2.10 Bio-Based Nanomaterials and Green Nanotechnology

In sustainable agriculture, the creation of bio-based nanomaterials is a potential concept. Compared to traditional nanomaterials, these materials are more environmentally benign because they are derived from natural sources like bacteria and plants. Innovative solutions for soil and water monitoring, accurate nutrient delivery systems and nano sensors are being developed using nanomaterials derived from biotechnology. Due to their biodegradability and low toxicity, they are perfect for use in sustainable farming, which lessens the need for dangerous pesticides and encourages environmentally beneficial methods (Zukowska *et al.*, 2024).

3 Future Perspectives

Sustainable agriculture must be viewed as an ecosystem approach in which biotic and abiotic living things coexist in harmony with food chains and the energy balances that accompany them. Government policies, specialization, modernization, greater use of nano chemicals and new technology are all modified to optimize agricultural output. In order to overcome the dilemma, the food business must implement the most recent technology. Consequently, nanotechnology is the new and future technology, with some unique properties in the food delivery chain like nano-pesticides, nano-fertilizers, nano-herbicides, precision farming techniques, value addition, etc. on a global scale. Research on agricultural nanotechnology or nanofoods may need to focus more on a few specific areas in the near future:

3.1 Combination of Precision Agriculture with IoT

The combined use of precision farming, the Internet of Things and nanotechnology helps in driving the next wave of agricultural innovation. Farmers will be able to maximize resource utilization and minimize waste thanks to the regular monitoring about condition of crops, environmental factors and soil health that is provided by nano sensors and Internet of Things devices. Additionally, this integration will make it easier to create intelligent agricultural systems that can modify inputs on their own by using data analytics (Alam *et al.,* 2024; Kansotia *et al.,* 2024).

3.2 Development of Smart Delivery System in Agriculture

Nano-formulations which release nutrients in reaction to the soil pH or moisture content can greatly improve nutrient utilization efficiency and reduce chemical runoff (Kansotia *et al.,* 2024; Alam *et al.,* 2024). Agrochemicals that are released by smart delivery systems with respect to specific stimuli are expected to gain traction. These systems will not only enhance the efficacy of fertilizers and pesticides but also minimize their environmental impact.

3.3 Focus on Biodegradable and Eco-Friendly Nanomaterials

For the eco-friendly environment, the biodegradable nanomaterials need to be developed, becomes the major concern for sustainable farming. In order to decrease the potential of sustained ecological damage, researchers are investigating the use of natural polymers, plant-derived nanoparticles and other sustainable sources to generate nanomaterials that can readily disintegrate in the environment (Żukowska *et al.,* 2024).

3.4 Nanotechnology-Driven Circular Economy in Agriculture

In agriculture, nanotechnology is essential to the advancement of the circular economy. It has the potential to reduce waste creation and more resource efficiency by facilitating the value-addition of food and agricultural waste. Nano catalysts, for instance, can enhance sustainable resource utilization by converting organic waste into biofuels and bio-based molecules. To further support the circular economy, nanotechnology can further improve the effectiveness of waste-to-energy conversion operations (Zukowska *et al.*, 2024).

3.5 Global Adoption and Policy Frameworks

It is anticipated that the use of nanotechnology would increase in underdeveloped nations as it develops. However, strong legislative frameworks and regulatory standards will be necessary for the broad adoption of farming methods made possible by nanotechnology. To provide uniform safety procedures and guarantee the wise use of nanotechnology in agriculture, government and international organizations will have to work together (Lallawmkimi *et al.,* 2025; Ullah *et al.,* 2024).

Conclusions

Sustainable farming is being transformed by nanotechnology, which provides creative solutions that maximize output, minimize resource use and lessen environmental effect. Improvements in AI-driven precision agriculture, smart nano fertilizers, nano sensors and nano-coatings allow farmers to produce more with less input, increasing agricultural efficiency and environmental friendliness. In the future, precision farming will be further fuelled by the combined use of nanotechnology, biotechnology, data analytics and artificial intelligence platform, which will allow for factual monitoring and predictive decision-building. Furthermore, the creation of climate-resilient crops and biodegradable nanomaterials will aid in tackling global issues like soil degradation, food security and climate change. Nanotechnology-enabled sustainable farming has great potential, but it still faces obstacles in the areas of cost, scalability, regulatory approval and possible environmental hazards. Responsible research, robust regulatory frameworks and cooperative efforts between scientists, legislators and farmers will result the broad application of nanotechnology in agriculture. Nano-enabled farming has the great impact on the future of agriculture, which will make it more robust, effective and future friendly as the result of research advancement. The use of nanotechnology can create a world that is smarter, greener and more food secure.

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