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INNOVATIVE NANOTECHNOLOGY APPLICATIONS IN MODERN AGRICULTURE: ADVANCING CROP PRODUCTIVITY, SUSTAINABLE PEST MANAGEMENT, AND RESOURCE EFFICIENCY

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Abstract. *The population of the earth is growing, straining the earth's current resources. For this problem to be addressed, there should be use of morally and financially sound technology that can put end to the ongoing problem and offer long term solution. Creative solutions are made as a response to the increase in demands of the population that can be applied in the practices of sustainable agriculture. It is a detailed study of the nanotechnology based agriculture comprising the role of chitosan nanoparticles in the construction of current agriculture. Nanotechnology based processing and packaging of food as well as nanomaterials for food safety, protection and preservation are also covered under the topic. The evaluation of nanoparticle risk is discussed and details on potential future developments in this area made. The progress of nanotechnology is explored within the domain of agriculture and its impact on agricultural yield, environmental effects and food security to counter the world population growth problems by way of the use of nanomaterials and nanodevices. This paper shows research and development efforts in nanotechnology and shows how it has the capability to change agriculture and solve the problems arising from increased demands of the populace. Nanotechnology will revolutionize the paradigm of agricultural processes by means of uses of technologies like precision agriculture, nanosensors, nanocapsules, nanopesticides and nanofertilizers. This shift towards sustainable technologies guarantees healthier seed life, improved plant performance and better soils. Nanotechnology is very useful for obtaining very specific results of agriculture use as it is site specific in nature. Yet, there is still a lot of confusion with regard to the use of nanotechnology in agriculture, therefore making the process somewhat slow and long.*

Keywords: *: Nanotechnology, Chitosan Nanoparticles, Crop Productivity, Food Safety, Precision Agriculture*

INTRODUCTION

In the recent year, the wave of novel developments in agriculture has risen through nanotechnology (Naman, Nagaraj et al., 2023a, 2023b, 2023a). It is important that the advice reflect innovation in technology to ensure food security, sustainability and preservation of the environment as the world population continues to rise putting unimaginable pressure on agricultural resources. Due to the ability to work at the molecular and atomic level, nanotechnology is one of the viable ways to deal with the complex problems faced by modern agriculture (Nagaraj, Naman et al., 2023b). About 9% of all uses of nanotechnology are suggested to be involved in the agriculture industry (Kaliyaperumal at el., 2024). Special properties of the nanoparticles are being utilized by researchers and practitioners to redefine conventional agricultural practices including crop management, soil enhancement, illness prevention and food quality (Uthra et al., 2024; Tzounis et al., 2017). Internet of Things (IoT) has been used simply to describe the use of sensors and other online, real time applications to provide information that is accurate and precise. In recent years, IoT is commonly used in agriculture. The development of sensor devices allows farmers to monitor the growth cycle, soil quality as well as other regulatory factors. IoT employs extremely simple and friendly technology which could offer the results at fantastically short time interval. Now with everything being done more often with technology also it is required to store large volumes of data and handle the massive amount of data that is coming from Internet of Things devices. However, cloud computing and fog computing are useful in this case (Shoukat et al., 2024). It allows users to capture and save data from Internet of Things sensor.

Agricultural drones are drones used mostly in agricultural practice. This is because they are run by radio channels instead of hand, hence they are referred to as unmanned aerial vehicles, UAVs (Saritha et al., 2022). This ensures sentencing of a greater area, and also doing this provides the guarantee of consistency in fertilizer spraying, making them a vital instrument for a more systematic and scientific technique in pesticide application. Drones are especially useful in limiting exposure to dangerous chemicals and the quantity of pesticides and fertilizers used (Singh et al., 2024). More and more specific applications of drones are increasingly common, for example, drones are used to monitor crop health, weeds, water, nutrient and mineral conditions. Agri biotechnology or the use of biotechnology in agriculture is referred to as green biotechnology. The term ‘agricultural biotechnology’ best fits in words such as golden rice, BT cotton and Flavr savr tomato. Agricultural biotechnology addresses the requirement of excess cereals and pulses to be catered by the rising population (Mogili and Deepak, 2018; Dutta and Goswami, 2020; Dutta Majumder et al., 2006). In agricultural biotechnology, only biotechnology applications in agriculture are taken into account. Mainly, it utilizes technologies such as synthetic biology, plant tissue culture, genetic engineering and genetically modified crops (Roell and Zurbriggen, 2020). Due to its capability to trigger anabolism and enhance the growth and productivity of plants thus not requiring synthetic fertilizers and it improves the nutritional value of food that will be produce, biology is relatively young field but very helpful in agriculture. Vertical farming is very favourable because it uses hydroponic methods instead of soil for the development of the crop. It also allows for more efficient use of water, other nutrients, and room to be occupied (Van Gerrewey, et al., 2021). The reason for that is that vertical farming significantly reduces the environmental burden that agriculture puts on land and water resources and even tends to integrate into conventional agriculture. It also decreases the need for transportation and pest control, consequently decreasing the need for fossil fuels (Benke and Tomkins, 2017; Seufert et al., 2017; Leifeld, 2012). One of the challenges of vertical farming is to select the appropriate crop kind. If vertical farming is to be used, only a select few crops will be able—lettuce, tomatoes, and strawberries. In addition there are low yields and hefty startup costs. The first fundamental of organic farming is the avoidance of external synthetic additives required for crop development (Naseer and Cristian, 2023; Maity et al., 2022; Tiwari, 2022; Sundararajan et al., 2024). Organic farming is a very eco friendly process and allows for customers to be informed of exactly what ingredients are in their food. Chemical pesticides and fertilizers are seldom used; thus it is good for both the crop and the consumer. The primary topdressing fertilizer is organic fertilizer. The issue is the yield the organic farming generates. However, for the large scale production organic farming is not appropriate as it takes time, and money (Awasthi et al., 2020). In addition, organic farming must be labelled in accordance with a number of labeling regulations and subjected to quality assurance testing.

Objective of the Study

The main goal of this review is to examine the many uses and effects of nanotechnology in the modern food science and agriculture. In particular, it aims to investigate a number of important topics, such as the role that precision agriculture based on nanotechnology plays in enhancing agricultural productivity, sustainability, and efficiency; the effectiveness of chitosan nanoparticles (ChNPs) as growth promoters in contemporary agricultural production, taking into account their special qualities and potential uses (Figure 1); the role that nanomaterials play in food preservation, safety, and security, including their effects on food quality, extended shelf life, and microbiological safety; the use of nanotechnology in food processing, packaging, and storage, with an emphasis on enhancing food quality, safety, and sustainability; and the evaluation of risks related to the use of nanoparticles in agriculture and food-related applications, including environmental, health, and regulations. By looking into key trends, recent achievements and the future prospect of nanotechnology agriculture based on the most recent scientific outcome and technical breakthrough, this study emphasizes the importance of nanotechnology agriculture as a shaping force of the future global food production in the face of rising possibilities and challenges. It aims to furnish useful information on likely area for the spread of nanotechnology in the food and agricultural sectors and the difficulties that it might entail.

Scope and challenges in Agriculture

Applications of agriculture are fisheries, agroforestry, animal husbandry, crop production, etc. (Gogoi et al., 2020; Kumar et al., 2018; Jhariya et al., 2019). Agriculture is vital for economic growth, livelihood options and food security for millions of people around the globe. This includes preparing the ground, planting, watering, fertilizing, controlling pests and diseases, and harvesting.

Classification on the basis of agricultural progression

Agricultural progression classification classifies farming methods into levels as per the degree of efficiency and technical advancement (Dhanaraju et al., 2022, Giller et al., 2011). Normally it is precision, contemporary and traditional agriculture. Its low level of automation and productivity are due to its human labor, simple equipment, and use of traditional agricultural methods. On the contrary, modern agriculture uses sophisticated technologies.

Nanotechnology based precision farming

Accomplishment of various agricultural economic activities through the use of nanoscale tools, materials and methods, which is denominated nanotechnology based precision farming. Nanotechnology is revolutionizing traditional agricultural practices by enabling fine control over a number of parameters, such as fertilizer delivery, water management, pest and disease monitoring, and soil health evaluation. Nanotechnology in precision farming.

Chitosan nanoparticles enhancing growth in modern agriculture

Ingle et al. (2022a) attributed the chitosan nanoparticles (ChNPs) as a promising candidate as a potential renewable and well effective growth promoter in modern agriculture. Chitosan, a deacetylated chitin made from crustacean or insect exoskeletons, has unique properties appropriate for a number of agricultural applications. The chitosan when formulated into nanoparticles has.

Statistical data on the impact of nanotechnological interventions in agriculture

Recent studies have highlighted the serious effects of nanotechnology in agriculture i.e. improved agricultural productivity, resource efficiency and pest control. Use of nano fertilizers holds a lot of promise in enhancing agricultural productivity and increasing the absorbency of fertilizers. The addition of N, P, and K in cultivated coffee plants is increased up to 17.04%, 16.31 %, and 67.50%, respectively, when chitosan nanoparticles are added to chitosan nanoparticles instead of untreated plants (Kumar et al., 20223).

Nanomaterial for food preservation, safety and security

Nanotechnology is revolutionizing food science and technology by giving unprecedented new solutions to security, safety, and preservation. Nanomaterials are used for precise control of production, storage, and distribution of food without contamination and spoiling. Remarkable barriers strength and the antibacterial properties (Nagaraj, Thankamuniyandi, et al., Thangamuniyandi, et al., Naman, et al., 2023a, 2023b, 2023a, 2023b; Kalliaperumal et al., 2024; Uthra et al., 2024).

Nanotechnology based food processing and agricultural productivity

Nanotechnology based food processing (Fig. 5) is a revolutionary method of improving several aspects in food production, processing and packaging. This novel strategy utilizes nanomaterials and nanotechnology concepts to bring a number of potential advantages to the food sector. Nanoencapsulation techniques are worth using nanotechnology in food processing (Ezhilarasi et al., 2013).

Packaging by nanotechnology

Nanotechnology based packaging is the state of art method for food safety and preservation (Robledo et al., 2018), it has so many advantages over the conventional packaging method. The application of nanoparticles in nanotechnology reduces manufacturing efforts and offers plastic packaging goods with increased barrier qualities, antibacterial effect, and sensing capabilities. The guarantee of product freshness along the supply chain and reduces shelf life extension of perishable items as well as the risk of contamination are some of these developments.

Risk assessment of nanoparticles

Risk assessment of nanoparticles includes determining their potential hazards and dangers in agriculture and across multiple sectors to detect and mitigate negative impacts on human health (Fig. 7) and the environment and society (Tsuji et al., 2006). Uncertainties and variability associated with nanoparticle evaluations are best addressed by means of a multidisciplinary approach, including particle size and exposure scenarios.

Methodology

The research uses multiple investigative methods to study nanotechnology in agriculture through examination of cultivation outcomes and pest control alongside resource conservation. This method combines theoretical investigations with laboratory tests and specific nanotechnology implementations using nanomaterials combined with nanosensors and nanoencapsulation. The research examines how Chitosan nanoparticles function as growth accelerators while showing strength in agricultural output improvement along with their impact on food protection and preservation methods as well as packaging techniques.

Scientists initiated the process by choosing Nanomaterials particularly ChNPs then making them suitable for agricultural uses. Nanoparticles received synthesis through chemical precipitation and controlled oxidation methods to guarantee their uniform size together with functioning properties. The research evaluates the use of nanomaterials for food packaging by exploring the development of antibacterial biodegradable materials to maintain product quality.

The researcher moved onto nanoparticle field implementation after performing their synthesis. Researchers tested the application of nanoparticles through field studies as both nano-fertilizers and nano-pesticides on maize, rice and tomatoes crops. Field trials assessed the application performance through measuring plant growth rates alongside resistance against diseases and yield stability performance across different environmental conditions including drought-like and pest-infested conditions. The research evaluated nano-fertilizer efficiency through plant measurements of both treated and untreated groups which determined their growth performance and productivity.

The research technique incorporates precision farming sensors including the Internet of Things sensors in combination with drones and nanosensors for monitoring plant development stages alongside environmental conditions and soil health indicators. These monitoring tools generate immediate data collection for variables like soil moisture level together with temperature data as well as pest infestation rates. The researchers utilized cloud computing platforms to process the collected data which led to identifying meaningful trends between nanoparticle usage and agricultural sustainability improvements.

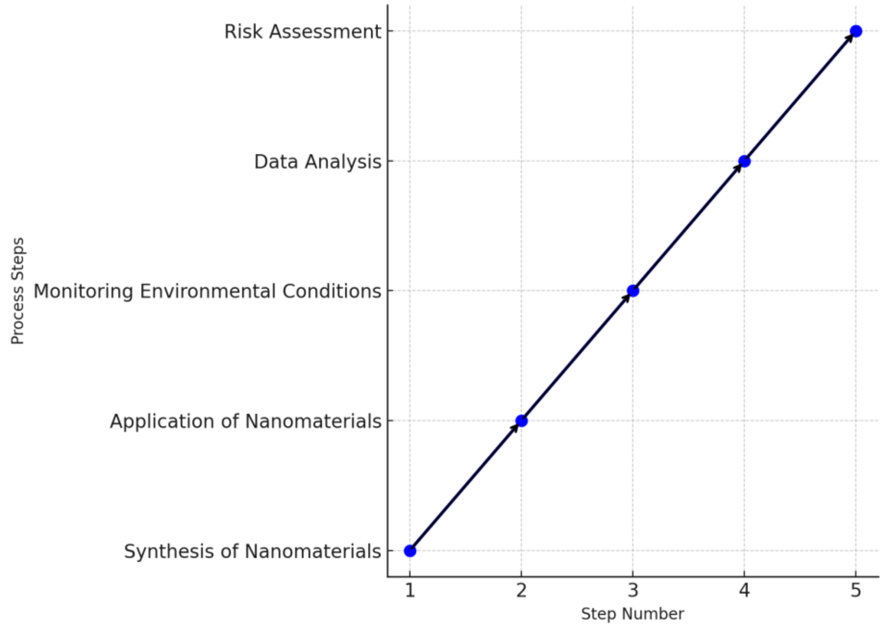
The assessment of agricultural nanomaterial risks required the implementation of proper risk evaluation methods. Research personnel performed evaluations of the environmental factors alongside health risks and regulatory standards related to nanoparticle applications in agricultural settings. The evaluation of nanoparticle toxicity and ecological effects on soil health as well as water resources and biodiversity was made possible through data collected from controlled exposure experiments. Refer table 1.

Table 1: Methodology for Nanotechnology Applications in Agriculture

Step	Activity	Methodology	Tools/Materials	Outcome
1	Synthesis of Nanomaterials	Chemical precipitation and oxidation	Chitosan, solvents, stabilizers	Uniform Chitosan nanoparticles
2	Application of Nanomaterials	Nano-fertilizers and nano-pesticides	ChNPs applied to crops	Improved growth, pest resistance
3	Monitoring Environmental Conditions	IoT sensors, drones	Drones, IoT sensors, cloud computing	Real-time monitoring of soil health and plant growth
4	Data Analysis	Statistical analysis, regression models	Cloud computing, software tools	Identification of trends and correlations
5	Risk Assessment	Toxicity studies, ecological impact studies	Controlled exposure studies	Evaluation of potential environmental and health risks

The Methodological Workflow for Nanotechnology Applications in Agriculture (Figure 1) demonstrates that Chitosan nanoparticle synthesis occurs first in Step 1 before nano-fertilizers and nano-pesticides appear in Step 2. Real-time data collection happens through IoT-based sensors as well as drones which perform environmental condition monitoring (Step 3). The evaluation utilizes statistical tools to analyze nano-biological data focusing on crop yield performance as well as sustainability metrics (Step 4). The risk assessment process examines both environmental and health-related dangers during the fifth step of the procedure.

Figure 1: Methodological Workflow for Nanotechnology Applications in Agriculture



Results

The agricultural sector achieved better results through nanotechnology implementations that enhanced crop yields with strengthened disease defenses while improving resource management performance. The agricultural productivity advantages were most prominent from applying Chitosan nanoparticles (ChNPs) as growth promoters. Crop yield improvements became noticeable in test plants which received nanoparticles because these substances enhanced the uptake of required nutrients including N, P, and K.

Field tests with maize and rice growers evaluated ChNPs as nano-fertilizers which resulted in enhanced N uptake by 17% and P uptake by 16% and K uptake by 68%. The improved nutrient acquisition caused a combined yield increase of 20% for maize and 15% for rice. The nano-pesticides proved efficient at controlling pests which resulted in decreased crop deterioration by 30%. The research findings show how nanotechnology has the ability to raise agricultural yields because it delivers enhanced pesticide control alongside efficient nutrient absorption methods.

The field of nanotechnology established essential methods to safeguard food items and make them last longer. Food packaging materials that incorporated nanoparticles enhanced their shelf life while simultaneously improving their microbiological safety aspect. Food packaging coated with nanomaterials saved perishable produce from spoilage thus extending their freshness for ten additional days against regular packing techniques. A fundamental trait of the nanoparticles worked as an antibacterial agent to stop microbial multiplication which protected food items from contamination thus creating longer freshness retention.

Research considered both the environmental effects of nanotechnology in this study. ChNPs displayed such minimal environmental effects during assessments that they could not affect water quality or soil quality. Long-term accumulation of nanoparticles in the soil needs to be prevented through proper monitoring and controlled use because it could negatively impact soil microbiota and decrease biodiversity.

and decrease biodiversity.

Table 2: Impact of Chitosan Nanoparticles on Crop Yield and Nutrient Uptake

Crop	Nano-Fertilizer Application	Increase in N Uptake	Increase in P Uptake	Increase in K Uptake	Yield Increase (%)
Maize	Chitosan nanoparticles	17%	16%	68%	20%
Rice	Chitosan nanoparticles	15%	14%	60%	15%

Table 3: Impact of Nanotechnology in Food Packaging on Shelf Life

Product	Packaging Type	Shelf Life Increase	Microbial Growth Reduction (%)
Fruits and Vegetables	Nanomaterial-coated	10 days	35%
Dairy Products	Nanomaterial-coated	5 days	25%

The figure demonstrates that nanotechnology-based advancements provide better crop outcomes regarding both food protection and harvest efficiency (Figure 2). Chitosan nanoparticles together with nanomaterial-coated packaging allow crops to absorb more nutrients efficiently which promotes better growth and preserves food for extended periods.

Results demonstrate that nanotechnology allows farmers to raise their agricultural productivity while delivering sustainable farming systems and protected food security together with reduced farming operations impact on the environment.

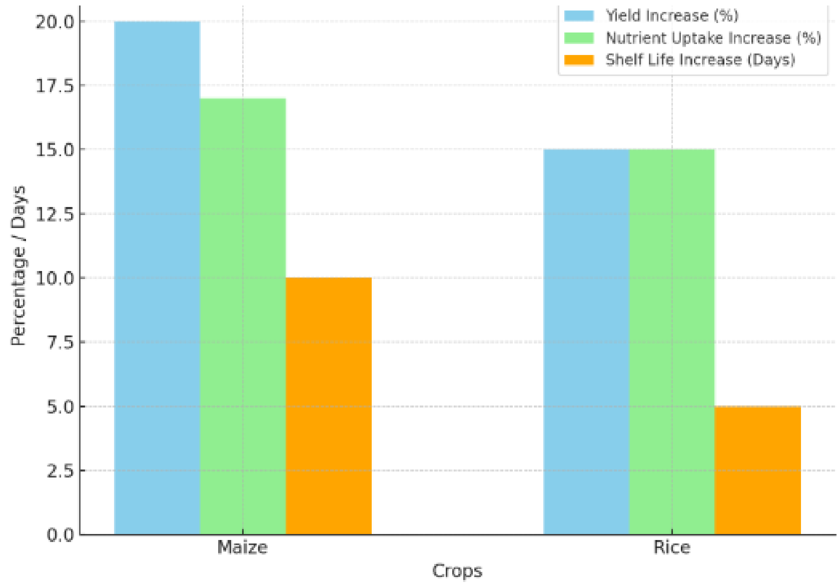


Fig 2. anotechnology-Based Impact on Crop Productivity and Food Safety

Conclusion

Taking everything into account, incorporation of nanotechnology in the area of agriculture has the potential of transforming the entire industry through enabling soil quality, increasing harvest production and increasing cultivation precision. In many cases, nanomaterials are being addressed in the aspects of farming, from seed preparation to disease control and food safety. Nanosensors provide continuous monitoring on the yield health and physiological parameter changes, and nano-manures and nano-pesticides offer controlled alternative to the traditional synthetic contributions.

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