FULafia Journal of Science & Technology
ISSN (print) 2449-0954 \ ISSN (online) 2636-4972
https://lafiascijournals.org.ng/index.php/fjst
Sponsored By TERTIARY EDUCATION TRUST FUND
Manuscript => Received: Jan., 2024; Accepted: April, 2024; Published: May, 2024
https://doi.org/10.62050/fjst2024.v8n1.267

APPLICATIONS OF NANOBREEDING FOR THE ENHANCEMENT OF FOOD SECURITY

S. A. Sirajo*, E. H. Kwon-Ndung and H. A. Kana
Department of Plant Science and Biotechnology, Federal University of Lafia, Nigeria
*Corresponding email: salamatusabdul@gmail.com

ABSTRACT
This review focuses on the pressing issue of global food security amidst population growth and environmental challenges. It underscores the significance of adopting innovative agricultural practices, particularly nanotechnology, to address these challenges. Nanotechnology offers promising solutions across various aspects of food security, including enhancing crop productivity, minimizing food waste, and ensuring sustainable agricultural practices. The review emphasizes the potential of nanobreeding, which involves utilizing nanotechnology tools to improve crop production and quality. Through nanoscale fertilizers, pesticides, sensors, and controlled release systems, nanobreeding offers targeted and efficient solutions for crop management. Moreover, nanopesticides and nano-fertilizers contribute to sustainable pest and disease management, further supporting food security efforts. Integration of nanotechnology into conventional agricultural practices presents a transformative approach to tackle food security challenges while minimizing environmental impact. In essence, nanotechnology in agriculture holds promise for optimizing resource utilization, promoting sustainability, and enhancing global food security.

Keywords: Nanobreeding, food security, nanosensor, nanofertilizer, nanopesticide

INTRODUCTION
The global population continues to grow and environmental challenges escalate, ensuring food security becomes an increasingly urgent concern. United Nations (2023) related that, as at September 2021, the world population was estimated to be around 7.9 billion people. With projections indicating continued population growth, which is expected to reach approximately 9.7 billion by 2050. And meeting the demand for food requires sustainable and efficient agricultural practices.
Farmers globally have concentrated most of their efforts on improving the yield of crops via extensive and intensive agriculture by implementing novel technologies and ideas. Though critical, but there is need to develop new technology that will enhance product output while reducing food waste in order to preserve a nation's sustainable living standards and improve food security (Fadiji *et al.*, 2022). It is justifiable that innovative technology has the potential to greatly impact food security by improving agricultural practices, increasing productivity, and reducing food waste (FAO, 2016).
Nanotechnology, the manipulation of matter on an atomic and molecular scale, has shown immense potential in revolutionizing various industries, including agriculture. By harnessing the power of nanotechnology, the challenges faced in crop production can be address and contribute to ensuring global food security (Prasad *et al.*, 2017). Nanotechnology is among the most promising alternatives for increasing food availability and developing new products related to water application, food, environment, agriculture, energy, electronics, and medicine. It is a rapidly growing field with novel food research and exclusive agricultural applications (Sadeghi *et al.*, 2017). In recent years, there has been growing interest in using nanotechnology to improve food production for food security because of its remarkable access that keyed into the four dimension of food security (food availability, access to food, food use/utilization and food stability) (FAO, 2016).
The aim of this review was therefore to showcase the recent applications of nano-breeding for the enhancement of global food security.

Nanobreeding
Nanobreeding (crop improvement using nanotechnology) involves the application of nanotechnological tools and techniques to enhance crop production and quality. Crop improvement using nanotechnology offers a promising approach to address the challenges of sustainable agriculture, by enhancing productivity while reducing environmental impact (Kanwar and Bajpai, 2020). For example, nanoscale fertilizers can be designed to release nutrients slowly and more efficiently, reducing waste and maximizing crop uptake (Madzokere *et al.*, 2021). Nanoscale pesticides and herbicides can also be developed to provide targeted and controlled delivery, reducing environmental contamination and minimizing the impact on non-target organisms (Hou *et al.*, 2021). Additionally, nanotechnology can be used to develop sensors and monitoring systems that can help farmers optimize crop growth and detect early signs of stress or disease (Shang *et al.*, 2019). Nanoscale materials can also be used to improve soil health and fertility, leading to better crop yields and quality (Mohammad *et al.*, 2020); others are work by Alaa and Tawfiq (2019), Farooq *et al.* (2016) and Hussain *et al.* (2019).

Nanoparticles

Siddiqui *et al.,* (2015) described nanoparticles as "magic bullets" that have unique physiochemical properties i.e., high surface area, and high reactivity; tunable pore size, and particle morphology. They are extremely small particles that have at least one dimension between 1 and 100 nanometers (nm). They can be made from a variety of materials including metals, ceramics, polymers, and semiconductors. Because of their small size, nanoparticles exhibit unique physical and chemical properties that are different from those of larger particles of the same material. These properties make them useful in a wide range of applications, including electronics, energy production and storage, drug delivery, and environmental remediation (Wang, 2014).

These particles are very attractive with the ability to handle biological system. Nanoparticles are found to be very suitable in sensing and detection of biological structures and systems (Siddiqui *et al.,* 2015). Nanoparticles designed to improve nutrient uptake, promote plant growth, and increase crop yields are called nanofertilizer, others are, nanopesticides, nanoformulators and nanosensors (Mittal *et al.,* 2020).

Food Security and Insecurity

Food security is attained when there is available, accessible, and affordable safe and nutritious food for all people at all times (Global Food Security Index, 2021). It is a fundamental human right and a key component of global sustainable development (SDG-Goal 2).

According to Food Systems Summit (2021), food security can be achieved when people have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life; and affected when variety of factors, such as climate change, natural disaster, conflict, and economic instability emerges. The four main dimensions of food security: Physical *availability* of food, Economic and physical *access* to food, Food *utilization* and *Stability* of the other three dimensions over time (Food Security Update, 2023)

On the other hand, WFP (2021) and FAO (2021) described food insecurity as lack of access to sufficient, safe, and nutritious food that meets the dietary needs and preferences of an individual or household. It can result from a range of factors, including poverty, high food prices, conflict, natural disasters, climate change, and inadequate social safety nets.

CONCEPTUAL FRAMEWORK

Nanosensors and Precision Agriculture

One of the key areas where nanotechnology is making a significant impact is in the development of nanosensors. These tiny devices can detect and monitor various parameters such as soil moisture, nutrient levels, and pest infestations at a much finer scale (Amin *et al.,* 2021). Yeshe *et al.* (2022) stressed that by deploying nanosensors in the field, farmers can collect real-time data and make informed decisions about irrigation, fertilization, and pesticide application. This precision agriculture approach helps optimize resource utilization, reduce waste, and enhance crop yields.

Precision agriculture aims to optimize crop production by utilizing technology and data-driven approaches. In recent years, nanosensors have emerged as a key component of precision agriculture, offering new possibilities for monitoring and managing agricultural systems at a microscale. The exploration of nanosensors and their applications in precision agriculture involves the use of nanoparticles as tiny devices that can detect and measure physical, chemical, or biological properties at the nanoscale (Bueno *et al.,* 2017). These sensors utilize nanomaterials, such as nanoparticles or nanowires, which possess unique properties due to their small size and high surface-to-volume ratio. Nanosensors can be engineered to respond to specific stimuli, enabling the precise monitoring of various parameters in agricultural systems (Ramesh, *et al.,* 2022).

Soil plays a critical role in crop growth, and its health directly impacts agricultural productivity. Nanosensors provide valuable insights into soil properties, allowing farmers to make informed decisions regarding irrigation, fertilization, and soil management (Yadav *et al.,* 2023). An example explained by Senapaty *et al.* (2023) was the use of nanosensors to measure soil moisture content, nutrient levels, pH, and salinity. Real-time data from these sensors enables farmers to optimize irrigation scheduling, improve nutrient management, and prevent soil degradation.

Nanosensors offer a non-invasive and real-time approach to monitor crop health. These sensors can detect indicators of plant stress, such as changes in chlorophyll levels, leaf temperature, or volatile organic compounds emitted by plants under stress (Buja *et al.,* 2021). By monitoring crop health parameters, nanosensors can assist in early detection of disease outbreaks, pest infestations, or nutrient deficiencies, allowing farmers to implement targeted interventions and minimize yield losses.

Beegum and Das (2022) states that, precision agriculture encompasses sustainable farming practices, and nanosensors contribute to environmental monitoring in agricultural systems. These sensors can measure parameters such as air quality, water quality, and pesticide residues. By continuously monitoring environmental conditions, nanosensors help farmers mitigate potential pollution risks, ensure compliance with regulations, and minimize the environmental impact of agricultural activities (Mohd *et al.,* 2021).

The data collected by nanosensors in precision agriculture needs to be effectively integrated and analyzed to derive actionable insights. Advanced data analytics techniques, including machine learning and artificial intelligence, can be employed to process large volumes of sensor data and generate meaningful recommendations (Shitharth *et al.,* 2021). Decision support systems can then provide farmers with real-time guidance on optimizing resource allocation, implementing precision treatments, and maximizing overall crop productivity (Yadav *et al.,* 2023).

Nanopesticides and Controlled Release Systems

Nanotechnology offers innovative solutions to address pest and disease challenges. Nanopesticides, formulated using nanoparticles, enable targeted delivery of active ingredients, enhancing their efficacy while reducing environmental impact (Wang *et al.,* 2022). Additionally, nanotechnology enables the development of controlled release systems, where nutrients or beneficial compounds can be encapsulated within nanoparticles and released gradually, ensuring their availability to plants over an extended period. This approach improves nutrient uptake efficiency, minimizes leaching, and reduces the need for frequent application (Wang *et al.,* 2022).

Pests and diseases pose significant challenges to crop production, leading to yield losses and reduced food security. In recent years, nanotechnology has emerged as a promising avenue for developing effective and sustainable pest management solutions

Nanopesticides refer to pesticide formulations that utilize nanotechnology to enhance their effectiveness and minimize their environmental impact (Chaud *et al.,* 2021). Nanoparticles, such as metal oxide nanoparticles or nanocapsules, are used to encapsulate active pesticide ingredients (Nuruzzaman *et al.,* 2016). This encapsulation offers several advantages, including improved solubility, controlled release, and targeted delivery.

Nanopesticides enable targeted delivery of active ingredients to specific plant tissues or pests, minimizing off-target effects and reducing the overall amount of pesticides required (Wang *et al.,* 2022). The nanoparticles can be functionalized to specifically interact with certain pests or plant structures, ensuring that the pesticide reaches its intended target (Chaud *et al.,* 2021, Deka *et al.,* 2021). This targeted delivery approach may improve the efficiency of pest control, reduce environmental contamination, and minimize the risk to non-target organisms.

Controlled release systems based on nanotechnology provide a novel approach to pesticide application. Nanoparticles can encapsulate pesticides and gradually release them over time, prolonging their effectiveness (Zhao *et al.,* 2022). This controlled release mechanism ensures a sustained presence of the pesticide at the target site, reducing the need for frequent applications (Hou *et al.,* 2021). By extending the duration of pesticide activity, controlled release systems improve pest management efficiency, reduce chemical inputs, and lower the risk of pesticide resistance development (Hou *et al.,* 2021).

Traditional pesticide application methods often result in excessive chemical usage and environmental contamination. Nanopesticides offer the potential to mitigate these issues. The targeted delivery and controlled release properties of nanopesticides reduce the amount of pesticides needed, minimizing their dispersion in the environment (Pradhan and Mailapalli, 2020). Furthermore, nanotechnology enables the development of biodegradable and environmentally friendly nanoparticle materials, further reducing the ecological footprint of pesticide applications (Anindita *et al.,* 2022).

Nanotechnology can enhance the efficacy and selectivity of pesticides. By encapsulating active ingredients in nanoparticles, their stability and solubility can be improved, resulting in enhanced efficacy against pests. Additionally, nanoparticles can be functionalized to specifically target pests or plant structures, increasing selectivity and reducing the impact on beneficial organisms. This targeted approach allows for effective pest management while minimizing negative impacts on ecosystems and biodiversity (Chaud *et al.,* 2021).

Nano-Fertilizers for Enhanced Nutrient Management

Conventional fertilizers often suffer from low nutrient use efficiency, leading to nutrient losses and environmental pollution. Nanotechnology provides a means of developing nano-fertilizers with enhanced nutrient delivery mechanisms (Jakhar *et al.,* 2022). Nano-fertilizers can encapsulate nutrients, protect them from degradation, and release them gradually based on plant requirements. Moreover, nanotechnology enables the functionalization of fertilizer surfaces, facilitating their interaction with plant roots and improving nutrient absorption. This targeted nutrient management approach promotes sustainable agriculture and minimizes the ecological footprint of farming practices.

Nano-fertilizers involve encapsulating nutrient particles within nanoscale materials, such as nanoparticles or nanocoatings. This encapsulation protects the nutrients from degradation, leaching, and volatilization, thereby extending their availability to plants (Nongbet *et al.,* 2022). Pravin *et al.* (2021) reported that controlled release mechanisms can be incorporated into nano-fertilizers, allowing nutrients to be released gradually based on plant demand. This controlled release approach ensures a sustained and targeted nutrient supply, minimizing nutrient losses and improving nutrient use efficiency.

Nano-fertilizers offer the potential to enhance nutrient uptake efficiency by plants. The nanoscale size of the particles allows them to penetrate plant tissues more easily, facilitating their absorption by roots, leaves, and other plant organs (Mohamed *et al.,* 2021). Abdel-Hakim *et al.* (2021) reported that, the surface properties of nanoparticles can be modified to improve their interaction with plant roots and enhance nutrient absorption. This increased nutrient uptake efficiency results in reduced fertilizer requirements, minimized nutrient losses, and improved plant growth and development.

Nano-fertilizers can be tailored to target specific nutrient deficiencies in plants. By encapsulating different nutrients within nanoparticles, it is possible to create multifunctional nano-fertilizers that address multiple nutrient requirements simultaneously (Yadav *et al.,* 2023). This customization allows farmers to provide plants with a balanced and tailored nutrient supply, promoting optimal growth and development. Moreover, nano-fertilizers can be engineered to release nutrients in response to specific environmental conditions, such as soil pH or moisture levels, further improving nutrient targeting and utilization.

Nano-fertilizers can positively impact soil fertility and health. The controlled release and targeted nutrient delivery provided by nano-fertilizers minimize nutrient leaching and runoff, reducing the risk of water pollution (Yadav *et al.,* 2023). This can aid in the gradual release of nutrients promotes microbial activity in the soil, enhancing nutrient cycling and organic matter decomposition. This leads to improved soil structure, nutrient availability, and overall soil health, creating a favorable environment for plant growth and nutrient uptake.

The use of nano-fertilizers offers several sustainability and environmental benefits. By improving nutrient use efficiency, nano-fertilizers reduce the amount of fertilizers needed, minimizing resource consumption and decreasing the environmental impact associated with fertilizer production and application (Yadav *et al.,* 2023). Moreover, nano-fertilizers exhibit controlled release properties, which means they release nutrients gradually over time. This characteristic reduces the need for frequent application, leading to decreased labor and energy demands. By adopting these sustainable practices, agriculture can achieve long-term sustainability while also addressing environmental challenges more effectively.

Transformation of conventional agricultural practices due to recorded cases of Nanobreeding.

As earlier stressed out, chemicals pose risks to both environment and human health, contributing to pollution and disrupting ecosystems, and in addressing these issues, farmers are turning to modern agricultural practices. These practices, including the use of nanoparticle-based technologies, offer more efficient, targeted, and environmentally friendly alternatives to conventional agrochemicals (Kah and Hofmann, 2014; Rico *et al*., 2011). By adopting these methods, farmers aim to reduce the adverse effects of traditional farming while promoting sustainable crop production.

Nanotechnology is like a super tool for making farming better. It includes tiny materials and gadgets that help with growing crops. These materials, like tiny bits of carbon-based nanomaterials, mineral nanoparticles, and metal/metal oxide nanoparticles, characterized by their remarkably high surface area, which makes them really good at doing specific jobs on a small scale (Stone *et al.,* 2010). For example, some of these tiny materials can help deliver nutrients directly to plants, which makes them grow better without harming the environment. They can also improve the way seeds grow and help plants deal with changes in the weather.

By using these tiny materials, farmers can reduce the need for harmful chemicals in their fields and grow crops more efficiently. Plus, they can make sure crops stay healthy and get all the nutrients they need without harming the environment (Martirosyan and Schneider, 2014).

These tiny materials can also be used to make sensors that help farmers keep an eye on their crops and make sure they're growing well. This helps farmers take better care of their fields and grow more food for everyone (Usman *et al.,* 2020).

In short, nanotechnology is like a secret weapon for farmers, helping them grow more food while being kinder to the environment.

RELEVANCE OF NANOBREEDING TO FOOD SECURITY

Crop improvement: As agriculture and food production change, nanotechnology has the potential to make a significant contribution. Nano breeding helps plants grow better by delivering nutrients and helpful substances directly to them. This means farmers can grow more food on the same amount of land (Kumari *et al.,* 2023).

Silver nanoparticle (AgNPs) has been shown to enhance seed germination and seedling growth in fenugreek (Sadak, 2019). They also exhibit antimicrobial properties, which can protect plants from pathogens. It has also been found that zinc oxide nanoparticle (ZnO-NPs) applications improved antioxidant response, and production of antioxidant enzymes. ZnO-NPs also had a beneficial impact on quite a number growth and yield parameters (Fazal *et al.,* 2023). Carbon nanotube (CNTs) as reported by Safdar *et al.,* (2022), shows the enhancement of plant growth by improving water and nutrient uptake, increasing photosynthetic efficiency, and stimulating antioxidant defenses

Pest and disease management: Nanotechnology creates powerful pesticides and fungicides that work better and cause less harm to the environment. These advanced products can target specific pests and diseases more effectively, protecting crops from damage and ensuring better harvests.

Silver nanoparticles (AgNPs) have been demonstrated to possess strong antimicrobial properties against a wide range of pathogens, including bacteria, fungi, and viruses (Bruna *et al.,* 2021). Copper nanoparticles (CuNPs) have demonstrated insecticidal activity against agricultural pests such as aphids and thrips, leading to reduced pest populations and crop damage another is study by El Saadony *et al.,* (2020) whom confirmed the biotransformation of copper nanoparticles (CuNPs) using a cell-free culture extract of metal copper-resistant bacteria *Pseudomonas fluorescens* MAL2, which was isolated from heavy metal-contaminated soils.

Improved crop quality and yield: Nanotechnology enables the development of crop varieties with enhanced traits such as disease resistance, shelf life, and nutritional content. By breeding crops with superior qualities, nanotechnology contributes to higher yields and better-quality produce, meeting the growing demand for food. nanopartitles such as zinc, boron, chitosan, and fertilizer nanocomposites such as ZnFe, MnB, NPK Mg, and calcite have been shown to significantly improve the vegetative and reproductive traits of fruit trees such as pomegranate, strawberry, mango, date, coffee and grape.

Sustainable agricultural practices: Nanotechnology offers sustainable solutions for crop production by reducing the need for chemical inputs, minimizing environmental pollution, and promoting eco-friendly farming practices. This supports long-term food security by preserving soil health, biodiversity, and ecosystem resilience. nanoparticles due to their compact size, ease of transport, ease of handling, long shelf life, high efficiency make it the preferred choice of farmers over other conventional products. Nanotechnology supports agricultural and alleviates environmental challenges by producing nano-pesticides and managing plant diseases. This communication deals with the role of nanoparticles in agriculture for sustainable environment (Hazarikha *et al.*, 2022).

The extensive applications of nanoparticles in the agricultural sectors cover nano biosensors, plant growth regulators, plant growth promoters, nanofertilizers, nanopesticides, nutrient management, and protection against phytopathogens (Mohana *et al*., 2020).

CONCLUSION

In conclusion, the review highlights the critical role of nanotechnology in addressing the challenges of global food security. By harnessing the power of nanoscale materials and technologies, agriculture can become more efficient, sustainable, and resilient in the face of increasing population and environmental pressures. Nanobreeding, in particular, offers innovative solutions for improving crop productivity, reducing waste, and mitigating the impact of pests and diseases on agricultural systems. The integration of nanotechnology into conventional farming practices represents a paradigm shift towards more targeted and environmentally friendly approaches to crop management. However, it is essential to consider the potential risks and ethical implications associated with the widespread adoption of nanotechnology in agriculture. Continued research, regulation, and collaboration among stakeholders will be crucial for maximizing the benefits of nanotechnology while minimizing its potential drawbacks. Therefore, nanotechnology holds tremendous promise for shaping the future of agriculture and ensuring food security for generations to come.

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