Science in One Health 2 (2023) 100020

Contents lists available at ScienceDirect

Science in One Health

journal homepage: www.journals.elsevier.com/science-in-one-health

Review

Nanoscience and technology as a pivot for sustainable agriculture and its One Health approach awareness

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ARTICLE INFO

Keywords:
Nanoscience
Technology
Agriculture
One Health approach
One Health awareness

ABSTRACT

Nanoscience and technology have shown promise in revitalizing the agricultural sector and industries. This tool has gained the interest of many researchers as it can be utilized to drive sustainable agriculture by suggesting long-lasting solutions to different problems in the agricultural space. However, there is a paucity of data on its health implications for the environment, plants, animals, and humans. This review evaluated the cost-effectiveness and productivity of nanoscience and technologies. The review highlighted the underlying health implications of nanoscience and technology from a One Health perspective.

1. Introduction

The growth of various crops and the breeding of animals are two common food provision practices in agriculture, contributing to the economic growth and prosperity of many developing nations. Scientists and engineers are using innovative techniques to enhance agricultural productivity as the world's population grows [1]. However, manipulating the environmental system for agricultural activities to meet human needs can harm ecosystems.

Over the past few years, the research and use of agricultural nanotechnology have both concentrated on sustainability challenges, crop enhancement, and increased productivity [2]. As a result of increasing hunger, undernourishment, and child mortality rates, agricultural nanotechnology is particularly relevant in developing nations [2]. As shown by increasing papers and patents, developed and rising nations, such as Germany, Brazil, China, India, France, and Korea, are increasingly interested in using nanoparticles (NPs) in agriculture.

The term "nanotechnology" encompasses a wide range of materials, devices, and applications that involve nanoscale phenomena. This review focuses on the specific impacts of NPs on agriculture and human health. With the modification of traditional techniques for environmental assessment and their use in production enhancement, nanotechnology can be employed to remodel agricultural divisions, helping to study the biochemical processes of crops [3]. Nanotechnology may significantly and rapidly impact the agro-value nexus more than environmentally friendly technologies and agricultural biotechnology. The technology allows synchronized public benefits and legal, moral, and environmental improvements [4]. Soon, nanoscale agrochemicals, such as nanofertilizers and nanopesticides, will become prevalent in agricultural practices worldwide. The treatment of wastewater, soil quality improvement, and crop output via sensors to identify pathogens are just a few of the many agricultural uses of nanotechnology [5,6]. Below are a few of the ways NPs have contributed to agriculture.

2. Impact of nanotechnology on plant, soil, and human health: One Health approach towards sustainable development goals for good health and well-being

2.1. The benefits of nanotechnology in agriculture

The advent of nanotechnology has brought significant advancements in agricultural practices, offering solutions to a few of the most pressing challenges faced by this sector today. Table 1 provides a comprehensive overview of the transformative potential of nanotechnology in the agricultural sector, highlighting its multifaceted applications in enhancing plant, soil, and overall health, from enhanced nutrient uptake and targeted delivery of agrochemicals to improved plant breeding and enhanced bioavailability of nutrients. This shows how developing

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https://doi.org/10.1016/j.soh.2023.100020
Received 30 January 2023; Accepted 13 July 2023
Available online 19 July 2023

Table 1
Multidimensional impacts of nanotechnology in agriculture. Summarizing a spectrum of benefits for crop production, food safety, and sustainability.

Benefits	Description
Enhanced nutrient uptake	Nanotechnology allows for the development of nanofertilizers, which enhance nutrient uptake by plants and reduce nutrient leaching, leading to improved crop yield and reduced environmental impact.
Targeted delivery of agrochemicals	Nanotechnology enables the targeted delivery of pesticides, herbicides, and other agrochemicals, reducing the amount of chemicals needed and minimizing their potential impact on non-target organisms and the environment.
Disease and pest management	Nanomaterials can be used for the targeted delivery of antimicrobial and antifungal agents, improving crop disease and pest management.
Drought and salinity tolerance	Nanotechnology can be applied to develop drought- and salinity-tolerant plants by enhancing their ability to cope with water stress, and improving crop production in challenging environments.
Enhanced food packaging	Nanotechnology can be used to develop advanced food packaging materials that provide better protection against spoilage, extend shelf life, and include sensors to monitor food quality, contributing to reduced food waste and improved food safety.
Precision agriculture	In precision agriculture, nanosensors and nanodevices can monitor soil conditions, crop health, and environmental factors in real-time, allowing for more informed decision-making and optimized agricultural practices.
Soil remediation	Nanomaterials can be used for the remediation of contaminated soils by adsorbing, degrading, or immobilizing pollutants, thus improving soil quality and facilitating the sustainable use of agricultural land.
Improved plant breeding	Nanotechnology can be applied to develop advanced plant breeding techniques, enabling the development of new plant varieties with enhanced traits such as improved resistance to diseases, pests, and environmental stresses.
Post-harvest loss reduction	Nanotechnology contributes to post-harvest loss reduction through improved food packaging, advanced sensors for monitoring food quality, and the development of coatings and treatments that extend the shelf life of fruits and vegetables.
Enhanced bioavailability of nutrients	Nanotechnology can improve the bioavailability of nutrients in food by encapsulating or modifying the structure of nutrients, potentially leading to more nutritious and functional foods.

nanofertilizers, nanomaterials, nanosensors, and nanodevices can revolutionize traditional agricultural practices, contribute to sustainable development goals, and promote better health and well-being.

2.2. Nanotechnology to control plant diseases

Approximately 20%–40% of the world's crops are killed annually by pests and viruses [7]. Contemporary farming depends primarily on using pesticides, such as insecticides, fungicides, and herbicides, among others. Pesticides that are environmentally friendly and cost-effective must be developed. Improved shelf life, toxic-free pesticides, and increased solubility of poorly water-soluble pesticides might all have good environmental consequences due to emerging ideas such as nanotechnology [8,9]. The relevance of agricultural nanotechnology for managing illnesses and safety has been reported by Gogos et al. and Sastry et al. [2,4]. Gogos et al. [2] demonstrated that using nanoscale formulations of copper and zinc oxides could effectively control fungal and bacterial diseases in tomato plants. In contrast, Sastry et al. [4] reported the successful use of silver NPs in controlling plant pathogens in rice.

Agricultural chemicals and nutrients may be supplied to plants under controlled conditions and gradually using traditional nano-based herbicides and insecticides [10]. Insect pests and host diseases may benefit from using NPs [11]. Plants may be protected using NPs in two distinct ways.

(a) NPs provide crop protection;
(b) NPs may be used as pesticide carriers and can be sprayed (Worrall et al.) [9].

2.3. Nanotechnology to improve the quality of soil and fertilizer distribution

Managing crops using nanotechnology is critical for increasing agricultural yields. Researchers use nanostructures and materials, such as quantum dots, carbon nanotubes, and nanofibers, to analyze soil quality and fertilizer dispersion. NPs aim to decrease the spread of contaminants, reduce nutrient loss, and boost quality and production with optimal nutrient application [12]. Using vermiculite, nanoclay, and zeolite in ecological agriculture could boost fertilizer effectiveness and crop output [13]. In ecological agriculture, sandy loam soils may be improved by adding inorganic amendments to minimize NH_4-N passage and increase N fertilizer production [14]. Sharma et al. [13] reported that adding nano-hydroxyapatite to sandy loam soils reduced NH_4-N leaching by 32% and increased N fertilizer efficiency by 21% [13]. Based on its chemical composition and NP form, nanoclay is divided into hectorite, montmorillonite, kaolinite, bentonite, and halloysite [13].

2.4. Impact of nanofertilizer usage on agricultural production

The exhaustive use of fertilizers to improve soil fertility has been shown to impact crop yields [14]. In a study by Basavegowda et al. [15], applying nanofertilizers resulted in a 20% increase in corn yield compared to traditional fertilizers [15]. Using nanofertilizers is essential for increasing crop yields, as it improves the distribution of fertilizers to plants and progressively manages the slow supply of nutrients into the soil in a carefully regulated manner, thereby preventing eutrophication and water pollution [15].

2.5. Nanotechnology to reduce post-harvest loss

Post-harvest losses of food in wealthy nations exceed 40%. In least developed countries, they are greater than 40% in the post-harvest and processing phases [16,17]. The assault of microorganisms may swiftly degrade newly harvested, high-moisture, unpreserved yields. Using newer and more modern technologies, including nanotechnology, may reduce post-harvest losses. This may decrease post-harvest losses by producing functional packing elements with the smallest amounts of bioactive chemicals, better gas and mechanical characteristics, and minimal influence on the sensing qualities of fruits and vegetables [18]. In a study conducted by Ribeiro et al. [19], the application of nanotechnology in the form of silver NPs (AgNPs) incorporated into chitosan films extended the shelf life of strawberries. The AgNP-chitosan films reduced weight loss, decay rate, and microbial growth, demonstrating a 48% reduction in decay rate compared to the control group [19].

Structural media are used to create edible coatings, which are applied to food as a liquid (carbohydrate, lipid, protein, or mixture). Foods treated with these agents are kept fresher for longer by reducing the development of microorganisms, preventing dehydration, shutting off respiration, improving texture, and preserving volatile scent components. For synthetic meals, nanocoatings of edible qualities may provide a barrier to gas and moisture exchange and the delivery of flavors, colors, enzymes, antioxidants, or browning-resistant compounds [19]. With this method, nanoscale coatings up to a thickness of five nanometers may be created [20]. Products from the horticulture sector often use edible coatings or thin films. Cost, ease of access, usable qualities, mechanical characteristics, photosensitive characteristics, fencing effect versus gas flow, the structural barrier to water migration, microbes, and sensory suitability all play a role in selecting a material for a particular application [19,21].

Using nanosensors for grain quality monitoring is another pivot for sustainable agriculture [22]. Thermal, chemical, or microbial contamination can be detected by the sensor's ability to detect environmental changes (temperature, oxygen exposure, and relative humidity). They may be used to deal with grains contaminated by fungi or insects [6]. In an experimental study by Gültekin et al. [23], a nanosensor based on zinc oxide (ZnO) NPs was developed to detect aflatoxin contamination in stored grains. The nanosensor exhibited high sensitivity and a rapid response time, enabling effective monitoring and management of grain quality. Another method is to utilize polymer NPs that react with volatile agents and other analytes in the surroundings of stored meals and, therefore, identify the decomposition source [23]. In a study by Tomić et al. [24], polyaniline NPs were synthesized and utilized as sensing materials for detecting the volatile organic compounds associated with food spoilage. Therefore, the NPs allowed for effective monitoring of food quality.

2.6. Nanotechnology to enhance food processing

The world's largest food corporations use various strategies to improve their products' quality, health, and nutritional content. The food industry requires newer technology to boost output, market cost, and quality. Nanotechnology has several applications in food production and processing, including nano-based food additives, nanosensors, nano-encapsulation, NP-based smart distribution systems, nano-packaging, pharmaceuticals and healthcare [24]. Newer gelation or viscosity-increasing agents, food texture manipulation, flavor encapsulation, and other aspects of industrial food processing using nanotechnology are gaining popularity [25].

In a study by Mustafa et al. [26], a nanosensor was developed to detect pathogenic bacteria, such as *Escherichia coli*, in food products. The nanosensor demonstrated high sensitivity, rapid response time, and selectivity, thus providing an effective tool for monitoring food safety and quality. Anti-caking chemicals, transporters for nutrient delivery, antibacterial agents, fillers for mechanical power and stability, and food nanosensing are employed in food processing to increase food value and security assessments, where nanomaterials are utilized as food additives [26]. In nutraceuticals, dietary supplements are produced with improved stability and bioavailability [25].

Tabanelli et al. [27] demonstrated the effectiveness of nano-encapsulation in improving the stability and bioavailability of curcumin, a natural bioactive compound found in turmeric with potential health benefits. Significantly enhanced solubility and absorption were shown by the nanoencapsulated curcumin, which subsequently led to improved bioavailability compared to non-encapsulated curcumin. Kampa et al. [28] investigated the use of nanotechnology in food texture manipulation by developing a fat replacer based on nanoemulsions. The nanoemulsion-based fat replacer successfully mimicked the sensory and rheological properties of full-fat mayonnaise, providing a healthier alternative with a reduced calorie content. These experimental studies demonstrate the potential of nanotechnology to enhance various aspects of food production, processing, and safety, supporting the statement that the food industry can benefit from implementing nanotechnology.

Currently, the emphasis in nanotechnology research is on the creation of new nano-agrochemicals, such as “nanopesticides” and “nanofertilizers” [27]. These materials may provide the controlled release of agrochemicals and the selective delivery of macromolecules. Incorporating nanoscale transporters and chemicals into fertilizers and pesticides may decrease the applied quantity without affecting production [28], and the use of nanoagrochemicals seems essential for advancing contemporary agriculture. The basic trophic level in the food chain is plants, the ecosystem's primary producers. However, the long-term exposure of plants to NPs may influence the food chain due to their bioaccumulation [29–31], and many studies have shown that NPs may be absorbed and stored in edible plant tissues [32–34]. These NPs, or metal ions, would accumulate in their original form. However, the physicochemical characteristics of these substances may differ [33,35,36].

Aside from these effects, NP buildup may disrupt plant physiological processes, influence the integrity of cell and organelle structures, and modify protein, lipid, and nucleic acid content by creating hydroxyl radicals [32,33,37,38]. To reiterate emphatically, the wide range of potential uses raises many ethical, ecological, health, and safety concerns, all of which must be considered [38,39]. Many speculative and unconfirmed claims about the detrimental health effects of NPs were observed [34,40]. Nanotechnology has become more popular with the creation of a range of NPs for agricultural businesses. A deeper knowledge of the specific benefits and downsides of using NPs in our daily lives is needed.

Researchers and professionals are concerned about the dangerous disposal of hundreds of tons of different NPs each year, despite the technology's great advantages. Managed objects such as atmospheric air, aquatic objects, soils, hydrobionts, algae, fungi, tissue of land plants, and land animal tissues) have recently been proven as places where NPs may be discovered [41,42]. Less research has been conducted on NPs in soil than on other potential sources of contamination. NPs may be collected and disposed of in the soil, which serves as both a source of nourishment and a sink.

2.7. The transfer of nanomaterials from the environment to animals or humans and health implications from a One Health approach

One Health approach recognizes the interdependence of human, animal, and environmental health and emphasizes the need for interdisciplinary collaboration to address complex health issues. Investigating the transfer of nanomaterials from the environment to animals or humans is crucial for understanding their potential health implications from a One Health perspective (Fig. 1).

2.7.1. Transfer through the food chain

Nanomaterials can enter the food chain when plants and crops absorb them from the soil or when animals consume contaminated food or water. The accumulation of nanomaterials in plant tissues and their subsequent ingestion by animals can lead to biomagnification with potentially harmful consequences for human health [30,31]. Understanding the bioaccumulation and biomagnification of nanomaterials in the food chain is essential for assessing their potential risks and developing strategies for mitigating them [32,33,37].

2.7.2. Transfer through air and water

Nanomaterials can be released into the environment through manufacturing, agricultural applications, and waste disposal [29,38]. Once in the environment, they can be transported through air and water, potentially exposing humans and animals to these materials. The inhalation of airborne nanomaterials or consumption of contaminated water can result in the uptake of nanomaterials into the body, with potential adverse health effects [41,42]. Studies on the environmental fate and transport of nanomaterials are essential to assess their potential exposure pathways and develop effective strategies for managing their environmental risks.

2.7.3. Occupational exposure

Farmworkers and other individuals involved in producing, handling, and applying nanomaterials in agriculture may be at risk of occupational exposure to these materials. Understanding this is crucial for developing appropriate safety guidelines and protective measures for industrial workers.

2.8. Negative health impacts of NPs

Despite advancements in nanotechnology, growing concerns about the potential environmental and negative health impacts of NPs have

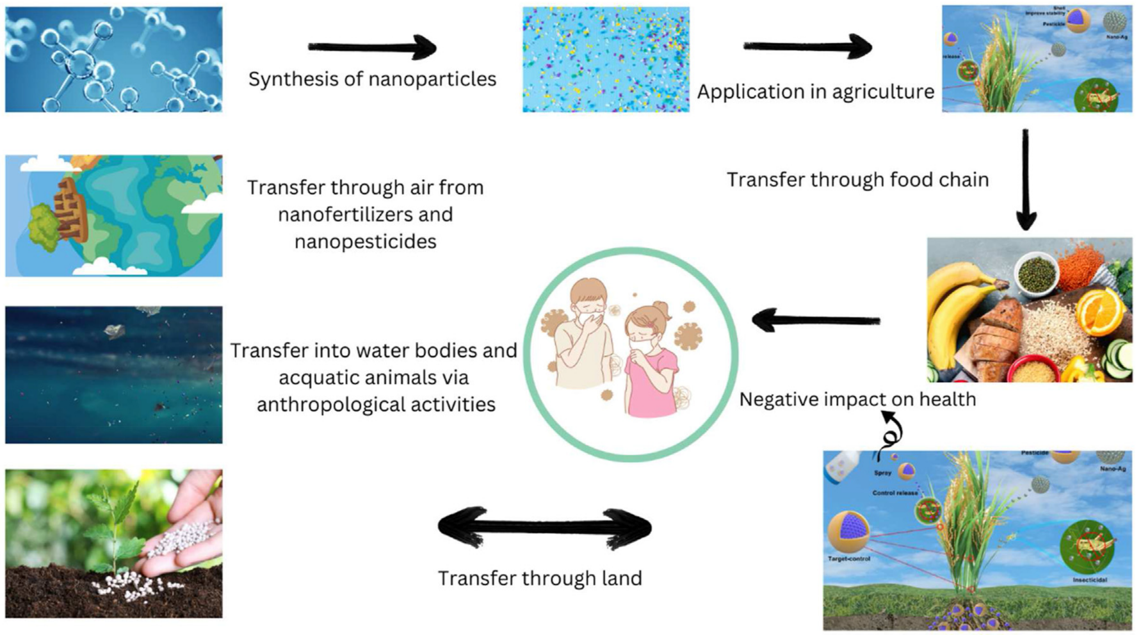

Fig. 1. Transfer of NPs via air, water, land, and into the food chain.

emerged. These concerns primarily arise from their ubiquitous presence stemming from anthropogenic activities. Upon their release into the environment, NPs can accumulate in the soil and subsequently be taken up by plants, which could lead to their introduction into the food chain, posing a potential risk to human health. Furthermore, specific NPs such as zinc and copper have been observed to induce biochemical changes that may harm human and plant health. Table 2 provides a concise summary of these negative health effects, highlighting the journey of NPs from their initial environmental release to their potential effects on human health.

2.9. Measures taken (or to be taken) to reduce the eco-toxicity of NPs

The use of nanotechnology in agriculture has gradually gained recognition. NPs have been recognized for their use in controlling pests and weeds and as antimicrobials in food packaging [60]. Amidst the benefits attained, NPs have been reported to have adverse effects on plants (Fig. 2), the environment (water, sediments, and soil), and human health (evidence of substantial buildup in the lungs, brain, liver, spleen, and bones) [61,62]. Therefore, it is necessary to address developing concerns to continue harnessing NPs.

In a study by Cai et al. [63] on the toxicity of metal oxide NPs, it was reported that surface passivation (coating) with ethylenediamine tetra (methylene phosphonic acid) led to a reduction in cytotoxicity and pulmonary inflammation in test cells and lung tissues [63]. Another study showed that the toxicity of tungsten carbide cobalt and cobalt on the crustacean *Daphnia magna* was delayed, and survival time increased after the NPs of concern were mixed with eco-corona biomolecule solution, and it highlighted that the biological degradation products (eco-corona biomolecules) present in natural ecosystems could reduce toxins. At the same time, NP uptake is not limited to use [64].

Given the outcomes of the aforementioned studies, toxins derived from NPs can be curtailed when potent inhibitors are involved, regarding the duration, distribution, and uptake of NPs noted per obtainable conditions [61]. In addition, changing the shape and size of particles and methods to adjust the surface can lead to NP formation with the required

Table 2
Summary of negative health impacts of NPs.

Health concerns and potential risk	Mechanism and impact details	Reference
Accumulation of NPs in soil	NPs can reach the soil through various anthropogenic activities and undergo transformations that increase their bioavailability and toxicity. Plants may take them up, becoming part of the food chain.	[38,43–45,47,48]
Release of NPs from nanofertilizers, nanopesticides, and nanotechnology cleanup	These processes introduce NPs into the environment, with the majority ending up in the soil and aquatic sediments. This can lead to environmental exposure and potential health hazards.	[39,46]
Bioavailability of NPs in soil	Soil qualities or components mediate the dissolution processes of metal-based NPs, making them more bioavailable and posing a higher environmental risk.	[33,48]
Uptake and accumulation of NPs in plant tissues	Plants take up NPs from the soil, causing them to accumulate in cells and organelles. These can then enter the human body via the food chain, posing a health risk.	[29,32,33,38,50]
Toxic effects of NPs on human health	The accumulation of NPs in human organs can cause stress responses, inflammation, weakened immunity, and potential disruption of regulatory systems. Additionally, NPs can cause damage to lung tissue in rats and brain damage in fish and dogs and have cytotoxic and genotoxic effects on human cells.	[42,49,51–59]
Toxicological effects of specific NPs	Zinc and copper NPs can pass through chemical and biochemical reaction pathways that may harm plant cells, disrupt nitrogen-fixing, and cause oxidative stress in human cells.	[29,59]

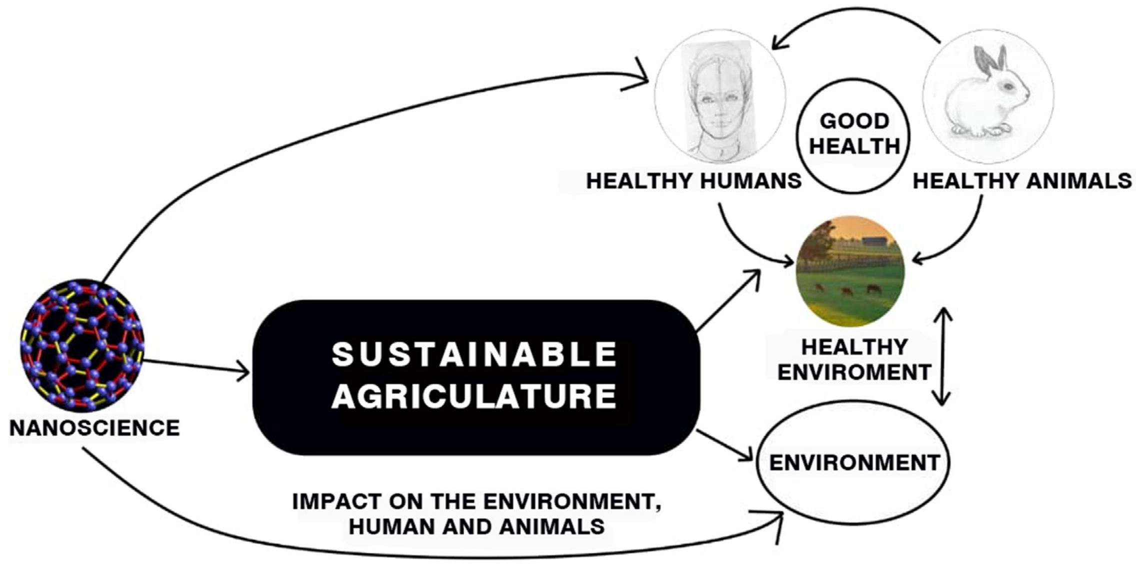

Fig. 2. The inter-related effects between nanoscience, technology, and life on earth.

properties without toxicity effects [65]. Temperature, pH of the reaction, the form of energy supply, choice of reagents, and reaction environment are conditions that affect the toxic properties of NP materials. During or after the combination process, substances that alter and soothe the exterior of NPs are typically added to the system [66].

Despite varying results, *in vitro* studies have been considered another mechanism to assess the level of nanomaterial toxicity. The most common approaches are tetrazolium reduction assays, cell membrane integrity with lactate dehydrogenase assays, immunohistochemistry biomarkers for apoptosis, and comet assays for genotoxicity [67,68].

Considering that most preventative approaches have been developed in the laboratory, Mittal et al. [69], in an analytical review, made recommendations to critically address challenges in understanding the gaps, practicality, and impact of environmental toxicity [69]. Equally, guidelines, regulatory bodies, and similar organizations to check for the sale of novel NP-based agrochemicals are vital. Lavicoli et al. [70] highlighted the need for more research in in-field settings to tackle nanomaterial toxicity [70]. The research focus should include competition with conventional formulations in terms of performance, cost, and scale manufacturing technology; the creation of new evaluation standards for nano-agrochemicals on product quality and safety; control systems to detect changes in environmental stimuli (such as pH, light, temperature, and enzyme activity); and the establishment of specific guidelines and effective large-scale field application technology for nano-agrochemicals to facilitate their extension in agriculture [71].

2.10. Challenges and the future perspectives of nanotechnology in agriculture

Despite the numerous advantages of using nanotechnology in agriculture, several challenges must be addressed for its effective implementation and widespread adoption. These challenges can be broadly categorized into environmental, health, and ethical concerns and practical issues related to the application of nanotechnology.

2.10.1. Environmental concerns

NPs have the potential to contaminate soil, water, and air, leading to adverse environmental impacts. The long-term effects of NPs on ecosystems and their potential to accumulate in the food chain are poorly understood. Further research is required to determine the fate, transport, and potential environmental risks of NPs in various agricultural settings.

2.10.2. Health concerns

The safety of NPs for human consumption is a critical issue that requires further investigation. The possible toxic effects of NPs on human health, particularly when ingested through food, must be studied thoroughly to ensure that nanotechnology-based agricultural products are safe for human consumption. Additionally, the potential occupational hazards for farm workers handling nanomaterials should be evaluated.

2.10.3. Ethical concerns

The application of nanotechnology in agriculture raises ethical questions related to the use of genetically modified organisms and the possible disruption of traditional farming practices. The potential social and economic impacts of nanotechnology on small-scale farmers and local communities must be considered to ensure that the benefits of this technology are equitably distributed.

2.10.4. Regulatory and standardization issues

Developing appropriate regulations and standards for using nanotechnology in agriculture is essential to ensure safety and promote consumer confidence. Regulatory bodies must establish guidelines for the testing, labeling, and marketing of nanotechnology-based agricultural products to ensure transparency and accountability in the industry.

2.10.5. Commercialization and scalability

Developing cost-effective and scalable methods for producing and applying nanomaterials in agriculture remains a significant challenge. In addition, ensuring the compatibility of nanomaterials with existing agricultural practices and infrastructure is crucial for their successful implementation.

2.11. Future perspectives

2.11.1. Increased interdisciplinary collaboration

Addressing the challenges associated with nanotechnology in agriculture requires the combined efforts of researchers from various disciplines, including materials science, agriculture, toxicology, and environmental science. Increased collaboration between these fields will enable the development of innovative solutions that balance the benefits of nanotechnology with its potential risks.

2.11.2. Development of advanced nanomaterials

A crucial role will be played by the design and synthesis of novel nanomaterials with improved properties for agriculture, such as enhanced biodegradability, reduced toxicity, and increased target specificity.

2.11.3. Adoption of a One Health approach

Considering the complex interplay between environmental, animal, and human health, adopting a One Health approach to assess the risks and benefits of nanotechnology in agriculture is essential. This holistic perspective will enable a more comprehensive understanding of the potential impacts of nanotechnology on agricultural systems and human health.

2.11.4. Enhanced public awareness and education

Promoting public awareness and understanding of nanotechnology and its applications in agriculture is vital for fostering informed decision-making and ensuring the responsible development and use of this technology. Educational programs targeting farmers, consumers, and policymakers can help build trust and facilitate the adoption of nanotechnology in agriculture.

2.11.5. Implementation of sustainable practices

The integration of nanotechnology into agriculture should be carried out in a manner that promotes sustainable agricultural practices, such as reducing pesticide and fertilizer use, conserving water, and enhancing soil health. This approach ensures that the benefits of nanotechnology are harnessed responsibly in an environmentally friendly manner.

2.11.6. Monitoring and evaluation

Establishing robust monitoring and evaluation systems to assess the long-term impact of nanotechnology-based agricultural interventions is crucial. This will enable the timely identification of any potential negative effects and will help with the development of appropriate mitigation measures.

3. Conclusion

Despite the information available on NPs, their risk assessment for human health has not been fully defined, as the toxicity of NPs depends on many factors, making it difficult to corroborate specific health hazards. This must be addressed before nanoscience and technology can be fully and safely exploited. Therefore, material researchers, agriculturalists, healthcare professionals, toxicologists, and environmental engineers must work together as an interdisciplinary unit or perspective to conduct multidisciplinary studies into the benefits and potentially harmful health effects and safety issues associated with NPs. Further interdisciplinary collaboration may engender a balance in NP usage, and it is widely known that most toxicity evaluation methodologies are based on the idea that chemicals may be detrimental to humans. Several physical and chemical features of nanomaterials may interfere with or complicate traditional toxicity assessments. In other words, unless lingering questions regarding NP fate, transport, and toxicity are answered, using NPs in the environment will likely remain controversial.

Funding

No funding was received for this research.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

Not applicable.

Authors' contributions

Goshen David Miteu conceptualized the topic/idea, wrote, supervised, revised, and approved the manuscript. All other listed coauthors participated equally in writing and approving the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to acknowledge "The Pan African Research Group" PARG and the Food and Agricultural Technology Unit of PARG for providing the platform for conducting this research. To our team lead, Elohozino Oghale Benneth, we acknowledge your instrumental efforts in ensuring this research's success.

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