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REVIEW

Green-Synthesized Nanomaterials for Aflatoxin Mitigation: A Review

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Abstract: Aflatoxin contamination poses a significant challenge to global food safety, public health, and agricultural sustainability. Traditional methods for mitigating aflatoxins, such as chemical and physical detoxification techniques, often raise concerns about environmental harm, nutrient loss, and potential toxicity. In contrast, green-synthesized nanomaterials have emerged as an environmentally friendly and effective solution for controlling aflatoxins. This study explores the potential of green-synthesized nanomaterials for aflatoxin mitigation, focusing on their mechanisms of action, effectiveness, and long-term applicability in agricultural and food safety contexts. A comprehensive review of 116 articles on the latest developments in green nanotechnology was used, focusing on the creation, characterization, and application of nanoparticles, including silver, zinc oxide, titanium dioxide, and iron-based nanomaterials. Green nanoparticles reduce aflatoxin load primarily through their antioxidant properties, which neutralize oxidative stress, and their high adsorption capacity, which binds aflatoxins and reduces their bioavailability. Photocatalytic degradation, adsorption, and enzymatic detoxification were also evaluated. The results indicate that green-synthesized nanoparticles exhibit high efficacy, biocompatibility, and minimal environmental impact, especially when compared to traditional detoxification methods. However, challenges such as nanoparticle stability, large-scale production, regulatory issues, and potential long-term toxicity still require further investigation. To advance this field, future studies should focus on refining green synthesis processes, enhancing nanoparticle stability, and exploring the integration of nanotechnology with biosensors and smart packaging for real-time aflatoxin monitoring. By advancing these sustainable technologies, this research aims to contribute to the development of effective and safe methods for aflatoxin mitigation, thereby supporting global food security, public health, and environmental sustainability.

Plain Language Summary: Aflatoxins are toxic substances produced by certain fungi, mainly *Aspergillus* species. These toxins contaminate food and animal feed, posing serious health risks and economic losses. Traditional methods to control aflatoxins, such as chemical treatments and pesticides, can be harmful to human health and the environment. Physical techniques like sorting, washing, and milling are not always effective. Researchers wanted to explore safer and more effective solutions.

Scientists investigated nanomaterials-tiny particles that can interact with aflatoxins in new ways, and they focused on three eco-friendly types:

- Silver nanoparticles (AgNPs)
- Zinc oxide nanoparticles (ZnO NPs)
- Carbon-based nanomaterials

These materials showed great potential for reducing aflatoxins by:

- Breaking down (degrading) 60-90% of the toxins
- Trapping (adsorbing) 50-80% of aflatoxins
- Stopping fungal growth by 70-90%

The study also examined eco-friendly coatings made from nanomaterials, and these coatings:

- Reduced *Aspergillus* fungi by 60-80%
- Helped food stay fresh 5 to 15 days longer

Thus, nanomaterials offer a promising, natural way to control aflatoxin contamination. Unlike traditional methods, they are safer for people and the environment. Using these materials could lead to healthier food, less waste, and better protection for farmers and consumers. More research and development could help bring these solutions to farms and food industries worldwide.

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Introduction

Aflatoxin contamination presents a major threat to global food security, public health, and agricultural sustainability, especially in staple crops such as peanuts, maize, and cereals.[1,2] Aflatoxins, produced by Aspergillus fungi, are highly toxic secondary metabolites that can cause serious health risks, including liver cancer, immune suppression, and hepatotoxicity.[3,4] These health risks not only affect human populations but also lead to significant economic losses, as aflatoxin contamination can decrease crop yields and quality.[5] Additionally, countries with high aflatoxin levels often face trade restrictions and export bans, limiting their access to international markets.[6] Conventional mitigation methods, including chemical treatments, physical decontamination, and genetic resistance, often have limitations due to environmental concerns, high costs, and partial effectiveness.[7,8] As a result, there is growing interest in eco-friendly, innovative solutions, particularly the green synthesis of nanomaterials for aflatoxin control. Green synthesis of nanoparticles involves using natural biomaterials to reduce metal ions into nanoparticles, characterized by techniques such as ultraviolet-visible spectroscopy and transmission electron microscopy. These nanoparticles are applied in fields like agriculture and medicine for purposes such as aflatoxin control and drug delivery. Green nanotechnology utilizes biological entities like plants, microorganisms, and biomolecules to produce nanomaterials in an environmentally friendly manner.[9] In contrast to conventional chemical synthesis, this approach minimizes the use of toxic substances, reduces harmful byproducts, and improves biocompatibility.[10,11] The resulting nanomaterials exhibit valuable properties, such as a high surface area, tunable reactivity, and strong adsorption capabilities, making them promising candidates for mitigating aflatoxin contamination.[12,13] Recent research has demonstrated that green-synthesized nanoparticles, including metal and metal oxide nanoparticles, carbon-based materials, and biopolymer composites, can effectively bind, degrade (60–90%), and inhibit aflatoxin (70–90%) production in food and feed systems.[14]

Despite these promising results, several unresolved issues remain regarding the use of green-synthesized nanomaterials for aflatoxin control. The precise molecular interactions between nanomaterials and aflatoxins require further investigation.[15] Additionally, variability in synthesis techniques, nanoparticle stability, and potential toxicity raise concerns about the large-scale application of these nanomaterials.[16,17] A thorough evaluation of the long-term environmental impact and biodegradability of these nanomaterials is essential to ensure their safety and sustainability for practical use. Furthermore, a robust regulatory framework and standardization are needed for the application of green-synthesized nanomaterials in food safety. Most studies to date have been limited to laboratory settings, with few field trials assessing their real-world effectiveness.[18] Additionally, the potential synergistic effects of combining green nanotechnology with other biocontrol methods have not been adequately explored.[19,20] Overcoming these research gaps through interdisciplinary collaboration is essential for advancing the use of sustainable nanotechnology in aflatoxin mitigation. This review focuses on the potential of green-synthesized nanomaterials for aflatoxin mitigation, highlighting their mechanisms of action, effectiveness, and long-term applications in agricultural and food safety contexts.

The Need for Eco-Friendly Approaches in Aflatoxin Control

Aflatoxin contamination poses a significant challenge to agricultural products, particularly in regions characterized by high humidity and warm temperatures.[21,22] Traditional methods used to control aflatoxin contamination predominantly involve the application of chemical treatments and physical removal techniques.[23,24] Chemical treatments often rely on synthetic fungicides designed to prevent the growth of *Aspergillus* fungi, the primary producers of aflatoxins (Figure 1). Physical methods, such as sorting, washing, and milling, attempt to remove or reduce contaminated portions of crops.[25,26] However, these strategies are far from perfect, as they fail to completely eliminate aflatoxins, and the repeated use of chemicals can be both expensive and inefficient over time.[27,28]

The environmental impact of traditional chemical control methods is a significant concern (Figure 1). The extensive use of synthetic fungicides and pesticides can damage ecosystems, leading to soil erosion and water pollution.[29] These

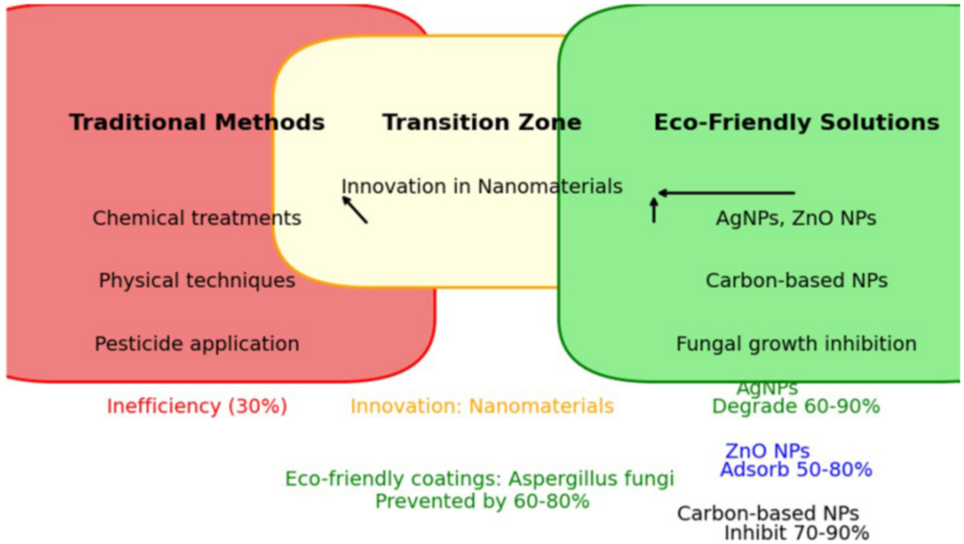

Figure 1 A comparative analysis of aflatoxin control methods: Traditional approaches vs Eco-friendly nanomaterial solutions.

chemicals often remain in the environment, contaminating soil and water, which poses a long-term threat to biodiversity.[30,31] Furthermore, indiscriminate use of chemicals can have detrimental effects on beneficial organisms, such as pollinators and other wildlife, disrupting ecological balance.[32] Over time, these practices can result in fungal resistance, diminishing the effectiveness of chemicals and requiring the use of stronger, potentially more harmful alternatives. Additionally, health risks associated with synthetic chemical treatments remain a significant issue, as residues from these chemicals may linger on crops, posing health threats to consumers and livestock that ingest them.[33] Chronic exposure to these toxic substances has been linked to a variety of health conditions, including cancer, reproductive disorders, and neurological damage.[34,35] This issue is particularly concerning in low-resource regions, where farmers may not have access to safety equipment or proper training on chemical handling. Consequently, toxic residues from aflatoxin-controlling chemicals can create a harmful cycle, negatively affecting both human and environmental health.[36]

Given the limitations of conventional approaches, there is an urgent need for eco-friendly methods of aflatoxin control. Alternatives, such as biocontrol agents, including beneficial microorganisms that naturally inhibit fungal growth, offer a promising and safer solution.[37] Other sustainable strategies involve the development of resistant crop varieties, improved agricultural practices like crop rotation, and ensuring proper storage conditions.[38,39] These methods reduce the environmental and health risks associated with chemical treatments, providing a long-term solution that prioritizes both food security and ecological preservation.[40] By transitioning to these sustainable practices, aflatoxin contamination can be controlled while protecting both human and environmental health.

Green-Synthesized Nanomaterials for Aflatoxin Mitigation

Green nanotechnology involves the creation of nanomaterials through environmentally friendly processes that reduce the use of harmful chemicals and minimize energy consumption.[41,42] It promotes sustainable and environmentally conscious methods in the production of nanomaterials. The core aim of green nanotechnology is to reduce environmental risks while enhancing or maintaining the performance and effectiveness of the resulting nanomaterials.[43] This field of study aims to develop nanoparticles that are not only effective for their intended applications but also safe for human health and the environment. In the case of aflatoxin control, green nanomaterials show considerable promise, as they can be designed to interact with aflatoxins and reduce their toxicity without relying on harmful substances.[44,45] Green-synthesized nanoparticles effectively control aflatoxins by inhibiting the growth of Aspergillus fungi and reducing aflatoxin production. Compared to conventional methods, they offer a safer, eco-friendly solution with minimal environmental impact. Their performance varies depending on the type of biomaterials used, but they consistently

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show promising results in reducing contamination and improving food safety. The synthesis of nanomaterials through eco-friendly methods typically involves biological, plant-based, and microbial techniques (Table 1). Biological synthesis utilizes natural resources such as plant extracts, algae, fungi, and bacteria, which act as reducing agents for metal salts or other raw materials.[46] Among these, plant-based methods stand out due to the natural compounds in plants, such as polyphenols and flavonoids, which aid in nanoparticle formation.[47,48] Polyphenols help in creating nanoparticles by acting as natural reducing and stabilizing agents, facilitating the synthesis of nanoparticles while preventing aggregation, thereby ensuring their stability and enhancing their bioactivity. Microbial processes are equally important, with bacteria, fungi, and yeast playing a key role in producing stable and functional nanomaterials.[49] These approaches not only minimize environmental impact but also enable the production of nanoparticles with specific properties, such as ideal shape, size, and surface characteristics, tailored for particular uses, such as aflatoxin reduction.

Numerous green-synthesized nanoparticles have demonstrated effectiveness in addressing aflatoxin contamination.[44] Silver nanoparticles (AgNPs), widely recognized for their antimicrobial qualities, have been found to effectively break down aflatoxins, providing a valuable tool for enhancing food safety.[54,55] Green-synthesized nanoparticles control aflatoxins by inhibiting the growth of Aspergillus fungi and reducing aflatoxin production without relying on harmful chemicals. As these nanoparticles are made from natural materials, they ensure food safety by targeting aflatoxin contamination while preserving the integrity of food products. Zinc oxide nanoparticles (ZnO NPs), another significant type of nanomaterial, possess antifungal properties and the ability to bind to aflatoxins, making them effective for eliminating aflatoxin-producing fungi in crops.[56] Titanium dioxide nanoparticles (TiO_2 NPs), known for their photocatalytic abilities, can break down aflatoxins when exposed to UV (Ultraviolet) light, offering a sustainable method to detoxify contaminated food and animal feed.[57] Moreover, carbon-based nanomaterials, such as carbon nanotubes (CNTs) and graphene oxide, have shown impressive capabilities in adsorbing aflatoxins, providing another promising option for reducing aflatoxin levels in agricultural products.[58]

Green-synthesized nanomaterials are pivotal in mitigating aflatoxins in food and agricultural systems.[59] They can interact directly with aflatoxins to degrade or absorb these harmful substances, ensuring safer consumption for both humans and animals. For example, silver and zinc oxide nanoparticles can be incorporated into food packaging to prevent aflatoxin contamination during storage, while carbon-based nanomaterials can be used in postharvest treatments to eliminate or neutralize aflatoxins.[60] Additionally, these nanomaterials can be applied in agricultural practices, such as soil treatments, to prevent fungal growth and ensure the safety of crops.[61] Hence, by incorporating these eco-friendly solutions, the detrimental effects of aflatoxins on food security and public health can be minimized, while fostering sustainable agricultural practices.

Mechanisms of Aflatoxin Degradation and Adsorption by Nanomaterials

Aflatoxins, produced by fungal species such as *Aspergillus flavus* and *Aspergillus parasiticus*, are hazardous toxins that commonly contaminate crops like peanuts, corn, and grains.[62] These toxins pose significant health risks, including liver damage and cancer. As awareness of the dangers of aflatoxins increases, there is a growing interest in innovative solutions to reduce their presence in agricultural products.[5] Nanomaterials, due to their unique properties, have garnered

Table 1 Comparison of Different Green Synthesis Methods Used for Nanomaterials (Plant-Based, and Fungal Synthesis Methods)

Plant Synthesis	Fungal Synthesis	Ref.
Occurs in chloroplasts, cytoplasm, and vacuoles.	Occurs in the cytoplasm and specialized structures.	[50]
Primary metabolites such as carbohydrates, proteins, and lipids.	Secondary metabolites like alkaloids, mycotoxins, and pigments.	[51]
Relies on photosynthesis (light energy).	Dependent on organic matter (decomposing substrates).	[49]
Mainly anabolic (building up molecules).	Involves both anabolic and catabolic processes.	[52]
Includes plant-specific enzymes like RuBisCO.	Involves fungal enzymes such as cytochrome P450.	
Primarily products used for growth and development.	Secondary metabolites used for defense and survival.	[53]

attention for their potential to degrade aflatoxins, absorb them, and inhibit the growth of aflatoxin-producing fungi, offering promising strategies to mitigate the risks associated with these toxins.[63]

One key method by which nanomaterials assist in the breakdown of aflatoxins is through their direct catalytic action.[15] Certain nanomaterials, such as metal nanoparticles (eg, zinc oxide and titanium dioxide), can facilitate chemical reactions that break down the molecular structure of aflatoxins.[64,65] This process involves the generation of reactive oxygen species (ROS) that damage the aflatoxin molecules, transforming them into less harmful byproducts.[66] The efficiency of this degradation process is largely due to the high surface area and reactivity of nanomaterials, which enable them to catalyze these reactions effectively.[67]

Another significant mechanism is the ability of nanomaterials to adsorb aflatoxins, effectively removing them from contaminated environments.[68] This adsorption process occurs due to the large surface area and porous nature of certain nanomaterials, such as activated carbon, silica nanoparticles, and carbon nanotubes.[69] Silica-based and clay-based nanoparticles effectively mitigate aflatoxins by adsorbing and neutralizing them, thereby reducing their bioavailability and toxicity in food and agricultural products. The surface properties of these materials allow them to interact with aflatoxin molecules through a combination of electrostatic forces, hydrogen bonding, and van der Waals forces.[70] This enables the nanomaterials to trap the toxins, reducing their concentration in contaminated food and feed, thereby improving safety.

In addition to degrading and adsorbing aflatoxins, some nanomaterials are effective in preventing the growth of aflatoxin-producing fungi, such as Aspergillus species. Nanomaterials like silver nanoparticles, copper oxide nanoparticles, and zinc oxide nanoparticles demonstrate antifungal properties that inhibit fungal growth.[71] These nanoparticles can interfere with the cell membranes of the fungi, causing damage that leads to cell death and preventing further toxin production.[72] By curbing fungal growth, these nanomaterials reduce the opportunity for aflatoxin contamination to spread, contributing to safer agricultural products.[73]

Thus, the application of nanomaterials in the fight against aflatoxins offers a multi-faceted approach that includes toxin degradation, adsorption, and fungal growth inhibition.[74] These mechanisms make nanomaterials highly valuable in addressing the persistent problem of aflatoxin contamination in food and feed.[75] However, for these methods to be successfully applied on a large scale, further research is needed to optimize the effectiveness, safety, and environmental impact of nanomaterials. With ongoing research and development, nanomaterials could play a critical role in ensuring food safety and mitigating the health risks associated with aflatoxin exposure.[76]

Applications of Green Nanotechnology in Peanut Production and Storage

Green nanotechnology presents a promising approach to advancing sustainable agricultural practices, particularly in peanut cultivation. During the pre-harvest phase, it can greatly enhance soil health and crop management.[77] Bio-based nanoparticles are applied during the pre-harvest stage to soil, seeds, and plant surfaces to prevent fungal infections by inhibiting Aspergillus growth. Delivered through foliar sprays, seed treatments, or soil amendments, these nanoparticles provide antimicrobial and antifungal effects, offering a sustainable and eco-friendly solution for controlling aflatoxins while preserving crop quality and safety. The application of bio-based nanoparticles also aids in the efficient delivery of nutrients to plants, enhancing fertilizer uptake and reducing the excessive use of chemicals.[78] Furthermore, nanotechnology enables the development of eco-friendly pest and weed control methods.[79] Nano-pesticides, for example, target specific pests with precision, minimizing harm to the environment and non-target species.[80] This approach ensures effective crop protection while promoting environmentally sustainable practices. Beyond crop treatment, green nanotechnology also plays a crucial role in the post-harvest phase, especially in enhancing peanut storage.[81] A major concern during storage is the contamination of peanuts by harmful fungi, including those that produce aflatoxins, which can compromise both safety and marketability.[82,83] Nanotechnology can be utilized to develop specialized coatings for peanuts that prevent fungal growth (Aspergillus fungi by 60–80%) and enhance shelf life.[84] These coatings are both antimicrobial and biodegradable, ensuring food safety while minimizing environmental impact. Such innovations help extend the storage period (5 to 15 days) without compromising quality (Figure 2). Most importantly, natural polymers and lipids, such as chitosan, alginate, cellulose, starch, gelatin, pectin, gum arabic, xanthan gum, chitin, phospholipids, essential oils, fatty acids, and triglycerides, can be used in the preparation of green nanoparticles for aflatoxin reduction.

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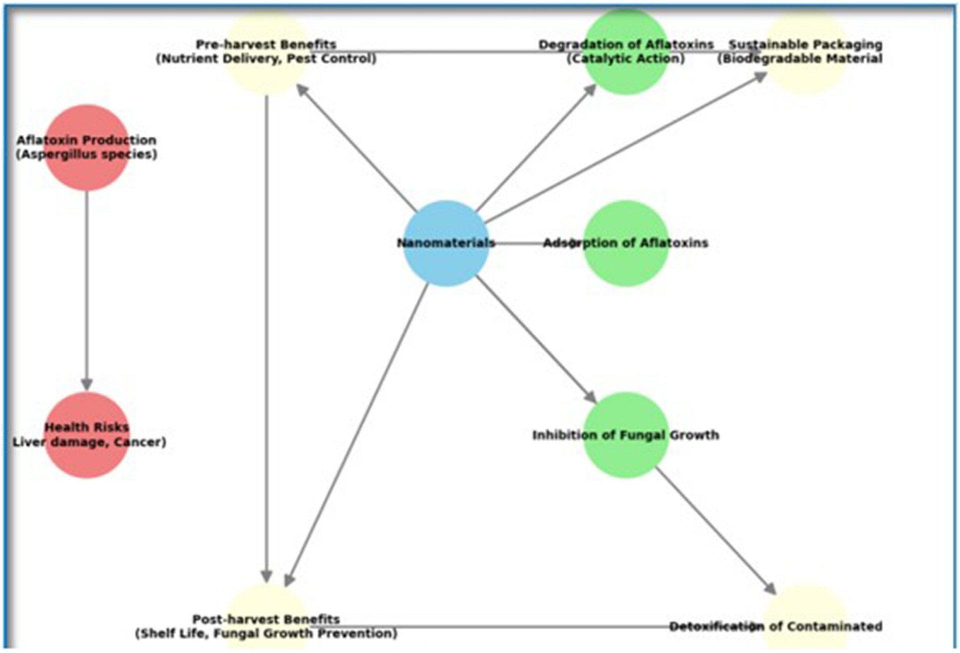

Figure 2 Nanomaterial solutions for Aflatoxin control in Peanuts.

Additionally, green nanotechnology offers the potential to revolutionize peanut packaging by introducing sustainable alternatives to traditional materials.[85] Nanomaterials, such as cellulose-based nanoparticles, can be incorporated into biodegradable packaging, offering both strength and environmental benefits.[86] This innovative packaging offers better protection for peanuts against physical damage and spoilage, while reducing reliance on plastic (Figure 2). Additionally, nanotechnology can aid in the detoxification of contaminated peanuts by removing harmful substances, such as aflatoxins, through nano-adsorbents.[87] Hence, by applying these technologies in both pre-harvest and post-harvest stages, green nanotechnology fosters a more sustainable and safer peanut production and storage system.

Safety, Sustainability, and Regulatory Aspects

Nanomaterials have gained significant attention for their innovative applications in food systems, such as enhancing food preservation, improving nutrient absorption, and advancing packaging solutions.[88] However, their small size and highly reactive nature raise concerns about potential toxicity. Due to their ability to easily penetrate biological barriers, these particles could lead to negative health effects, such as inflammation, oxidative damage, or DNA (Deoxyribonucleic Acid) alterations.[89] While extensive research is being conducted to understand their safety, there remains some uncertainty regarding their long-term impact on human health. Thorough testing, including laboratory and field studies, is essential to ensure that the benefits of these materials outweigh any potential risks.[90]

In addition to the direct health implications, the environmental impact of nanomaterials used in food and agriculture must be carefully assessed. When released into the environment through packaging degradation, pesticide applications, or fertilizers, nanoparticles may interact with soil, water, and living organisms.[91] Due to their small size and high mobility, nanoparticles can penetrate ecosystems more easily than larger particles, posing potential risks to plant and animal health. Studies indicate that certain nanoparticles may accumulate in natural environments, which could interfere with ecological processes.[92] Therefore, it is crucial to assess their environmental impact and develop solutions that minimize their effects, such as biodegradable or less harmful alternatives. The use of nanomaterials in agriculture also faces regulatory challenges due to the absence of consistent global standards.[93] Countries have adopted different approaches to regulating nanomaterials some classify them as new and distinct entities, while others integrate them into existing regulatory frameworks. The wide variation in nanomaterials, including differences in size, surface charge, and chemical composition, adds further complexity to regulatory evaluations.[94] Traditional testing protocols may not adequately account for these differences, leading to uncertainty in safety evaluations.[95] Establishing international standards and more specific regulations will be key to ensuring nanomaterials are used safely in agricultural practices.

The acceptance of nanotechnology in the agricultural and food industries is influenced heavily by public opinion.[96] While these materials can offer several advantages, such as improving food quality and extending shelf life, there are concerns about their safety and potential hidden risks.[97] Educating the public and increasing transparency regarding the science behind nanomaterials is crucial in gaining trust.[98] It is essential to reassure consumers that comprehensive safety assessments are conducted. Furthermore, collaboration among agricultural stakeholders such as producers, researchers, and policymakers is crucial to ensure that nanotechnology is applied responsibly and regulated effectively to address public concerns.[99]

The production of nanomaterials itself can present environmental challenges. Conventional manufacturing methods often rely on energy-consuming processes or the use of hazardous chemicals, which may not align with sustainability goals.[100] However, more eco-friendly production methods are being explored. For example, bio-inspired or green synthesis techniques using plant extracts, fungi, or bacteria offer a promising approach to producing nanomaterials with minimal environmental impact.[101,102] Additionally, conducting life-cycle assessments of nanomaterials can help identify areas for improvement in terms of reducing waste and energy use.[103] The future of nanotechnology in food and agriculture will rely on developing production methods that are both sustainable and efficient. The integration of nanomaterials in food systems and agriculture offers exciting opportunities but also presents significant challenges.[104] While the potential for enhancing food quality and agricultural productivity is clear, the safety, environmental impact, and regulatory complexities must be addressed systematically (Figure 3). Striking a balance between harnessing the advantages of nanotechnology and protecting public and environmental health demands extensive research, robust regulations, and clear communication.[105,106] As understanding in this field progresses, maintaining a focus on sustainable practices is crucial to ensure that nanomaterials enhance agricultural development while safeguarding human and environmental well-being.

Future Prospects and Challenges

The potential of green nanotechnology for mitigating aflatoxin contamination in peanuts is highly promising, driven by innovations in environmentally safe materials that can effectively target aflatoxin-producing fungi. By utilizing natural, non-toxic substances to create nanoparticles, green nanotechnology offers an eco-friendly solution compared to

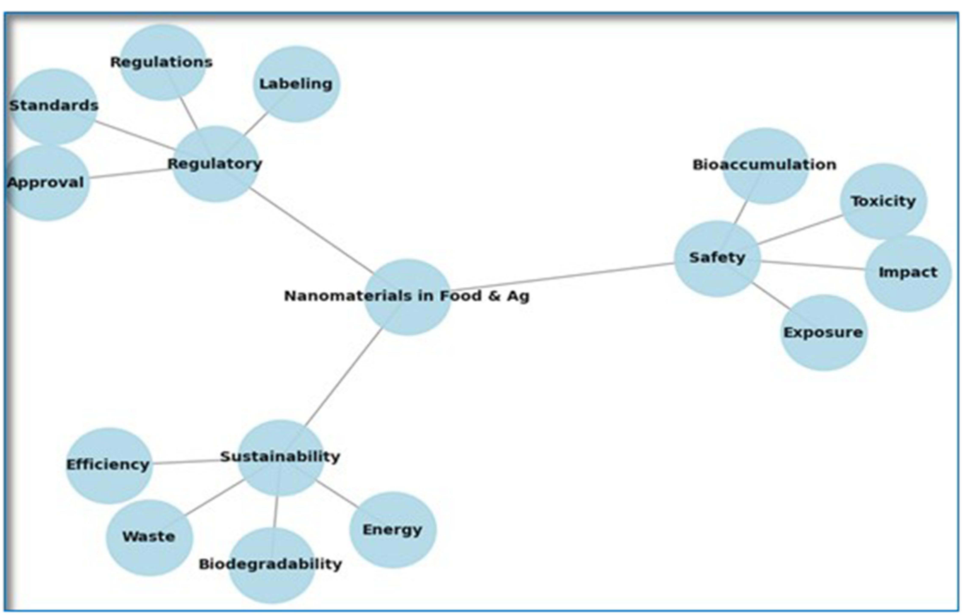

Figure 3 Fundamental aspects of nanomaterials in food and agriculture (Food &Ag).

Table 2 Future Prospects and Challenges in Green Nanotechnology for Aflatoxin Mitigation

Challenges	Proposed Solutions	Ref.
Low stability of Green-synthesized nanoparticles.	Surface modification with biopolymers.	[113,114]
Regulatory concerns.	More toxicity studies.	[115]
Cost of large-scale production.	Green chemistry optimization.	[116]

traditional chemical methods.[107] These nanoparticles can disrupt the growth of *Aspergillus flavus*, the fungus responsible for aflatoxin production, by interacting with its biological processes. Ongoing research and development are refining and applying these nanomaterials, potentially offering more efficient, safe, and sustainable approaches to combating aflatoxin contamination in peanuts.[108]

Combining green nanotechnology with other sustainable strategies, such as biocontrol agents and smart packaging, could further strengthen efforts to reduce aflatoxin risk. Biocontrol, which uses natural microorganisms to suppress harmful fungi, can complement the action of nanoparticles by providing an additional layer of protection against contamination.[109] Additionally, the integration of smart packaging technologies, capable of monitoring and adjusting storage conditions, could help prevent conditions that promote aflatoxin development.[110] This integrated approach could revolutionize the storage and transportation of peanuts, ensuring both safety and minimal environmental impact.

Despite the promising outlook, the large-scale implementation of these technologies faces several challenges. One of the primary concerns is the economic viability and scalability of green nanomaterials for widespread use, as producing these nanoparticles in bulk must be both cost-effective and environmentally safe.[11] Moreover, ensuring the stability of nanomaterials under varying environmental conditions such as humidity and temperature is crucial for their effectiveness in real-world storage scenarios.[111] Regulatory hurdles and public perception will also play a role in determining the adoption of these technologies (Table 2). Nonetheless, continued research could overcome these obstacles, leading to safer peanut production and storage practices that are both efficient and environmentally friendly.[112]

Conclusion

Green-synthesized nanomaterials offer a sustainable and innovative approach to reducing aflatoxin contamination in food and feed. Unlike conventional chemical detoxification methods, these nanoparticles are derived from natural sources, such as plants and microbes, making them more environmentally friendly and safer for both human and animal consumption. Their large surface area and reactive properties allow them to effectively adsorb (50–80%), degrade, or neutralize aflatoxins through processes like photocatalysis, biosorption, and enzymatic breakdown.

The application of these nanomaterials extends across various sectors, including food preservation, animal feed detoxification, and soil remediation. Different types of nanoparticles, such as silver (Ag), zinc oxide (ZnO), titanium dioxide (TiO_2), and iron-based nanomaterials, have demonstrated high efficiency in mitigating aflatoxin risks. However, their effectiveness is influenced by factors such as stability, synthesis conditions, and interaction with food components.

Despite their potential, main challenges must be addressed before large-scale implementation. Issues related to scalability, cost-effective production, regulatory approval, and long-term safety assessments remain critical. Establishing standardized synthesis protocols and conducting rigorous toxicity studies are essential to ensure their safe integration into food systems. Additionally, combining nanotechnology with biosensors, biopolymer-based coatings, and smart packaging solutions can enhance aflatoxin detection and prevention strategies.

Future advancements should prioritize refining green synthesis techniques, enhancing nanoparticle stability, and exploring synergistic approaches that integrate biological control agents. Collaboration among researchers, policymakers, and industry leaders is essential to facilitate the transition of these innovations from research to practical applications. By advancing eco-friendly nanotechnology, we can develop sustainable and effective solutions for aflatoxin mitigation, promoting safer food systems, improved public health, and environmental conservation.

Data Sharing Statement

Data sharing is not applicable to this article as no new data were analyzed in this study.

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Author Contributions

Both authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare that they have no conflicts of interest or personal relationships to disclose.

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