Review Article

Nanoformulations Use for Control of Fungal Contamination and Mycotoxins Production in Cereal Crops: Advances, Mechanisms and Future Prospects

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Abstract | Toxigenic fungi, particularly *Aspergillus*, *Fusarium*, and *Penicillium* species, pose a persistent threat to global cereal production by generating mycotoxins that endanger food safety and human health. Traditional control methods often fail to provide long-term and environmentally safe solutions. The aims of this review are to advance the field by delivering a targeted, up-to-date use of nanotechnology applications for preventing fungal contamination and mycotoxins build up in cereals, emphasis mechanistic insights, comparative advantages over conventional methods, and actionable knowledge gaps. It critically evaluates the antifungal and antimycotoxigenic properties of key nanomaterials such as silver, zinc oxide, copper oxide, titanium dioxide, and iron oxide nanoparticles, emphasizing several mechanisms of action, including membrane disruption, oxidative stress induction, and inhibition of mycotoxin biosynthesis. The potential of biopolymer-based nanocarriers and green-synthesized nanoparticles for sustainable and eco-friendly management practices is also discussed. Particular attention is given to their integration with pre-harvest, post-harvest, and packaging systems. While nanoformulations demonstrated promising results in wheat, maize, and rice systems, this review underscores the need for comprehensive biosafety evaluations, standardized regulatory frameworks, and environmental risk assessments. This review is a critical evaluation of studies conducted on use of nanoformulations in management of fungal contamination and mycotoxins production in cereal crops. Moreover, it emphasizes their practical use in providing grains without residues and having extended shelf life, which is a key for food safety and health. Nanotechnology offers a green technology to address toxigenic fungi as climatic changes continue to rise and alter agricultural ecosystems.

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Introduction

Cereal crops, including wheat, rice, and maize represent the main food sources of carbohydrates, proteins, vitamins, and major minerals in human and animal diets globally (Meza *et al*., 2025). Nonetheless, in addition to their food properties, grains are highly susceptible to fungal infection and accumulation of toxins in their layers (Abd-Elsalam *et al*., 2017; Arata *et al*., 2024). Mycotoxin-producing fungi, including species of the genera *Aspergillus*, *Fusarium*, and *Penicillium* produce secondary metabolites such as aflatoxins, fumonisins, ochratoxin A, deoxynivalenol, and zearalenone (Awuchi *et al*., 2021; Gurikar *et al*., 2023). These compounds show high levels of toxicity to human, including hepatotoxic, mutagenic, teratogenic, and immunosuppressive properties, and pose high dangers to food safety globally (Awuchi *et al*., 2022; Olariu *et al*., 2025). An estimated 25-50 % of global production of grains is contaminated with mycotoxins (Wang *et al*., 2022). Traditional antifungal treatments and chemical fungicides have been ineffective in offering sustainable protection and, in some cases, pose concerns related to environmental impact and safety (Islam *et al*., 2024). Thus, the need to create innovative, ecofriendly, and potent antifungal strategies is a pressing task.

Figure 1 provides an overview of the major toxigenic fungi, key nanomaterials with antifungal and antimycotoxigenic activity, their mechanisms of action, and their integration into sustainable pre-harvest and post-harvest management strategies.

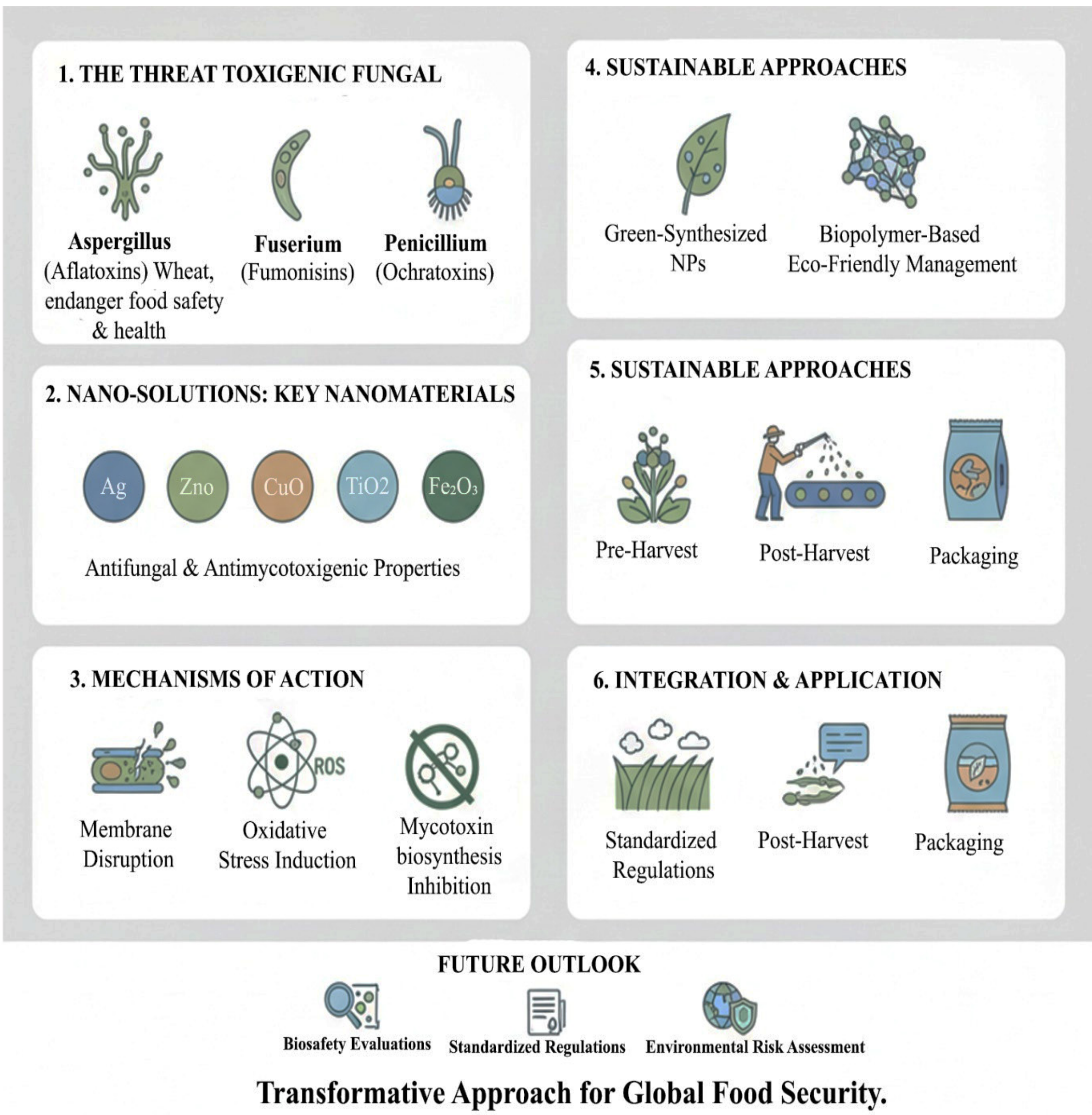

Figure 1: *Nanotechnology for cereal biocontrol: Mitigating fungal and mycotoxins threats.*

Nanotechnology presents one such innovative strategy, with the ability to create sophisticated materials with antifungal properties to control fungal growth and mycotoxins production throughout the processing of cereals (Mateo *et al*., 2025). Nanostructures, such as nano-silica, metal, metal oxide nanoparticles (NPs), and polymeric nanocomposites exhibit distinct physicochemical properties, including high surface area, reactivity, and sustained release, which may further potentiate the antifungal properties (Gacem and Abd-Elsalam, 2022; Yadav *et al*., 2025). These materials interact with fungal cell membranes, hinder spore germination, and suppress mycotoxins production. Furthermore, their application in coatings, storage, and biosensor development helps in detecting the antifungal agents or mycotoxins contamination in a real-time throughout the food chain (Sharma *et al*., 2025).

Antifungal NP approaches contribute to food security through the prevention of fungal infection and mycotoxins production, along with the minimization of synthetic pesticides and supporting environmentally sustainable agricultural practices (Cardoso *et al*., 2025). Understanding of antifungal mechanisms, antifungal efficacy, and biosafety is important to bring innovative laboratory results into practical and implementable solutions to secure safely consumed cereals (Medina *et al*., 2017).

Recent advances in management of toxigenic fungi combine biological, physical, and nano-based strategies. Examples include the use of biocontrol agents (Thipe *et al*., 2020; Ogwu and Izah, 2025; Yousef *et al*., 2025), essential oils (Bouqellah *et al*., 2025), antifungal nano-coatings and sensors made from NPs further improve detection and control measures (Dube and Okuthe, 2025), and biosynthesized metal NPs with remarkable antifungal and antimycotoxigenic potentials against key genera, such as *Aspergillus*, *Fusarium*, and *Penicillium* (Hashem *et al*., 2022; Wen *et al*., 2023). These findings support the growing relevance of nano-enabled solutions in cereals protection.

The objectives of the current review are to provide recent advances on synthesis of nano-systems used as antifungals and antimycotoxins in cereal systems, consolidates mechanical evidence, appraises performance of various nano-formulations, and outlines their uses in pre-harvest, post-harvest, and packaging as well. Specific attention is paid to safety, toxicity, and environmental concerns, filling existing gaps and offering a more understandable template for future research and actual practice (Figure 1).

Major toxigenic fungi and mycotoxins in cereal systems

Aspergillus spp. and aflatoxins

Globally, *Aspergillus* species are considered as the primary toxigenic fungi affecting cereal production, due to their production of aflatoxins (AFs), hepatotoxic, and carcinogenic compounds (Mesterhazy *et al*., 2022). The major AF producers are *A. flavus*, followed by *A. parasiticus*, while other species including *A. nomius* also produce aflatoxins in lower amounts (Abdel-Nasser *et al*., 2022; Gachara *et al*., 2024).

A. flavus is known to frequently infests maize, wheat, sorghum, and groundnuts, with AFB1 being the most toxic and frequently occurring. It belongs to Group 1 human carcinogens, which cause hepatotoxicity and immunosuppression (Rai *et al*., 2024). Many countries around the world experience periodic aflatoxins contamination due to fungal appropriate climatic factors, including high temperatures of 36-38°C and high humidity level above 85%, (Diener *et al*., 1987; Keller *et al*., 2022). There are four AFs; AFB_1, B_2, G_1, and G_2 distinguished by their fluorescence and chromatographic properties. Warm, damp, and slightly acidic conditions are strong determinants of aflatoxin's production by aflatoxigenic *A. flavus,* and several studies have demonstrated a large increase in aflatoxin's levels when the climatic and storage conditions are appropriate (Gwad *et al*., 2024).

Moreover, the high levels of *Aspergillus* contamination observed in Egyptian grains can be attributed, in part, to storage under conditions of elevated humidity and inadequate air circulation. Furthermore, data confirm the existence of such levels in Africa, where AFs contamination exists at high levels with considerable repercussions on food security and health (Wagacha and Muthomi, 2008; Meijer *et al*., 2021).

Fusarium spp. and their mycotoxins

Fusarium species are the most important toxigenic fungi in the production of mycotoxins contaminated grains, contributing to remarkable economic losses, due to their production of various toxins such as deoxynivalenol (DON). Trichothecenes (T-2, and HT-2 toxins), fumonisins (FBs), and zeareleone

(ZAN), posing appreciable threats to both yield and food safety (Perochon and Doohan, 2024).

Mycotoxin's profiles and pathogenicity

There are several major groups of mycotoxins produced by *Fusarium* species, each with distinct biological functions. The *F. graminearum*–*F. culmorum* complex is primarily associated with the production of deoxynivalenol (DON) (Zhen *et al.*, 2024), whereas *F. verticillioides* and *F. proliferatum* are high producers of FBs (mainly FB1). T-2/HT-2 type A are largely species-specific (e.g., *F. sporotrichioides* and other related species) (Ropejko and Twarużek, 2021), while Zearalenone (ZEA) is synthesized by a broader group of *Fusarium* species. Notably, these toxins act as virulence factors: DON and FB_1 suppress the host immune system, and host plants respond using detoxification enzymes and resistance genes (e.g., *TaFROG*, *TaSnRK1-alpha*, and *TaNFXL1*). Comparative evidence indicates that the toxin class has a strong influence on pathogenic strategies and host defense pathways of plants (Perochon and Doohan, 2024). A confirmatory study revealed the pervasive nature of *F. graminearum* in Egyptian and global food systems, often contaminating wheat, maize, and barley (Gavrilova *et al.*, 2023). High-performance liquid chromatography–tandem mass spectrometry (HPLC-MS/MS) and quantitative polymerase chain reaction (qPCR) analysis revealed the levels of DON, ZEA, T-2, HT-2, and FB contamination in grains in diverse regions, with DON being the most abundant (Gavrilova *et al.*, 2023; Borowik *et al.*, 2024). In the Urals and West Siberia, 16 species of *Fusarium* have been detected, with *F. sporotrichioides* and *F. avenaceum* being the most abundant. Parallel studies in Sichuan Province revealed the pre-eminent fungi in wheat and maize to be *F. asiaticum* (nivalenol, NIV chemotype) and *F. graminearum* (15-acetyldeoxynivalenol, 15-ADON chemotype) (Gavrilova *et al.*, 2023).

More advanced analytical tools such as Liquid chromatography–tandem mass spectrometry (LC–MS/MS), Chromatography–mass spectrometry (GC–MS), and electronic noses enhanced with machine-learning algorithms have remarkably improved the detection of *Fusarium* toxins, achieving recall efficiencies of up to 94% in both contaminated and uncontaminated grains (Borowik *et al.*, 2024). Although these technologies offer a high level of accuracy in mycotoxin identification; however, their costs, limited field portability, and the need for specialized expertise reinforce the growing importance of nano-enabled detection systems.

Nanomaterial-based sensors including nanoparticle-modified electrodes, nano-enhanced e-noses, and plasmonic or carbon-nanotube biosensors provide rapid, sensitive, and on-site detection capabilities that can be used in complement to or in place of traditional analytical techniques (Borowik *et al.*, 2024). Such advancements are particularly vital given the frequent co-occurrence of multiple *Fusarium* mycotoxins in agricultural commodities. Therefore, nanotechnology-driven monitoring strategies and the resulting nano-mediated control measures are increasingly necessary.

Penicillium spp. and associated mycotoxins

Penicillium species are soil-borne and storage fungi contaminating a wide array of agricultural commodities, such as grains, nuts, and dried fruits. Among them, certain species produce toxic secondary compounds (*i.e.*, OTA, patulin, citrinin, and roquefortine C); with deteriorating effects on food quality and safety (Abramson, 2020; Otero *et al.*, 2020). There have been identified two species of *Penicillium*, including *P. expansum* and *P. verrucosum*, known to produce OTA, whereas *P. citrinum* and *P. roqueforti* produce citrinin and roquefortine C, respectively (Deligeorgakis *et al.*, 2023). OTA is identified as being both nephrotoxic and hepatotoxic, with carcinogenic and immunosuppressive effects due to prolonged dietary exposure (Deligeorgakis *et al.*, 2023). *Penicillium* species, particularly *P. verrucosum* are frequently associated with contamination of stored cereals, such as wheat, barley, and other grains stored under suboptimal conditions (Alkuwari *et al.*, 2022). A recent systematic review (2013–2023) identified *Penicillium* as a major contaminant of cereal-based products worldwide, including flours and bread, with occasional occurrences of OTA levels exceeding safety limits in certain regions (Deligeorgakis *et al.*, 2023). Although OTA concentrations generally remain below regulatory thresholds, environmental surveys continue to detect *Penicillium* species in cereal storage ecosystems (Alkuwari *et al.*, 2022). Meanwhile, volatiles produced by *Cyberlindnera jadinii* have been shown to suppress *Penicillium* growth, highlighting their potential as biocontrol agents (Alkuwari *et al.*, 2022).

Mycotoxins derived by fermentation with *Penicillium*, like MPA, CPA, and ROQ-C have been found in cereals in combination, showing that several low-priority toxins can co-exist in cereal matrices (Topi *et al*., 2022). Their status as minor contaminants have traditionally been viewed as minor; however, the fact that these compounds do occur in some cases at quite high levels underscores the emergence of food-safety issues due to *Penicillium* metabolites. Most of these metabolites have not been regulated, although not shown under standard monitoring initiatives. This highlights the necessity of more extensive surveillance measures and modern regulatory consideration. Table 1 lists a summary of the major toxigenic species, their accompanying mycotoxins, and their host crops. These findings underscore the continuous threat of OTA and the growing realization of the roles of *Penicillium*-derived compounds, which have not been previously regulated in food webs.

Cereals-specific challenges in mycotoxins contamination

The sensitivity of cereal crops to fungal infections and mycotoxins accumulation depends on the crop species, the environment, and post-harvest storage. The major mycotoxins involved in contamination of cereals include AFs, OTA, FB, DON, and ZEA, mostly produced by *Aspergillus* and *Fusarium* spp. (Grenier and Applegate, 2013).

Wheat: Wheat is also susceptible to the prevalent causative mycotosigenic fungi; mainly Fusarium head blight (FHB), *Fusarium graminearum*, and *F. culmorum*, causing wheat contamination with T-2 mycotoxins, including DON and its acetylated products, and nivalenol (NIV). High humidity and warm temperature during anthesis favor disease severity. The fungal colony is most prevalent in the grain germ and crease area, and the level of mycotoxins rises with the long storage time and conditions of low ventilation (Portell *et al*., 2020; Pastuszak *et al*., 2021).

Maize: Maize is the most susceptible cereal to contamination with mycotoxinic *Fusarium verticillioides* and *F. proliferatum*, which produce FB_1, FB_2, and *A. flavus*, producing aflatoxins (Gachara *et al*., 2024). These toxins are frequently co-occurring during a hot and dry climate, especially when drying is not fast. Accumulation of mycotoxins highly depends on crop management practices instead of physiology of the kernels, with *F. verticillioides* becoming the most prevalent in later stages of the kernels growing (Arata *et al*., 2024). High amounts of FB exceeding EU concentration are a common issue of maize in Africa, Asia, and the Mediterranean region, highlighting current food safety concerns (Jedidi *et al*., 2021).

Table 1: *Comparative profiles of the key toxicogenic fungi and their mycotoxins in cereal systems.*

Fungal genus	Species	Major mycotoxins produced	Mechanism of toxicity/ mode of action	Optimal environmental conditions	Main cereal hosts	Health and economic impacts	References
Aspergillus spp.	*A. flavus, A. parasiticus,* and *A. nomius*	AFs (B_1, B_2, G_1, G_2)	Disrupt protein synthesis, induce oxidative stress and DNA damage, and hepatotoxic and carcinogenic activity	33–38°C, RH > 85%, and poor storage aeration	Maize, wheat, sorghum, and peanuts	Liver cancer, immunosuppression, growth retardation, and recurrent contamination in Egypt and Africa	(Abdel-Nasser *et al*., 2022; Keller *et al*., 2022; Gwad *et al*., 2024; Gachara *et al*., 2024)
Fusarium spp.	*F. graminearum, F. culmorum, F. verticillioides, F. proliferatum,* and *F. avenaceum*	DON, T-2, HT-2), ZEA, and FB_1, FB_2	Inhibit protein and sphingolipid biosynthesis, cause oxidative stress and apoptosis in plants, and estrogenic and neurotoxic potential in mammals	15–28°C, humid or rainy flowering, and drought stress before harvest	Wheat, barley, maize, oats, and rice	FHB, yield loss, feed refusal, reproductive toxicity, and cancer risk	(Jedidi *et al*., 2021; Gab-Allah *et al*., 2022; Perochon and Doohan 2024; Borowik 2024)
Penicillium spp.	*P. verrucosum, P. expansum, P. roqueforti,* and *P. citrinum*	OTA, Citrinin, Patulin, Roquefortine C, and Mycophenolic acid (MPA)	Inhibit protein synthesis and mitochondrial respiration, nephrotoxic and hepatotoxic potency, and chronic exposure linked to carcinogenicity.	10–25°C, RH > 80%, and damp storage and poor ventilation	Wheat, barley, maize, oats, and rice	Chronic kidney disease, carcinogenic potential, and post-harvest spoilage losses	(Otero *et al*., 2020; Alkuwari *et al*., 2022; Topi *et al*., 2022; Deligeorgakis *et al*., 2023;)

Where; This table represents the most important interrelationship between Aspergillus, Fusarium and Penicillium species, environmental preference, types of mycotoxins, toxicological processes. and health effects in the cereal systems.

Rice: Rice, representing the second most popular cereal in the world, is getting exposed to aflatoxins and OTA. The Chinese and Vietnamese surveys revealed that the prevalence of *Fusarium*-associated mycotoxins, including ZEA, DON, FB, and beauvericin has been practiced (Phan *et al*., 2021; Santos *et al*., 2022; Qiu *et al*., 2024). The agro-ecological zone affects the *Fusarium* communities, where *F. proliferatum* is most common during harvest and storage conditions, whereas *F. asiaticum* and *F. graminearum* are more common in the field (Xu *et al*., 2021).

Barley: Barley has a mycotoxin side view similar to wheat; mainly associated with DON and NIV produced by *Fusarium graminearum* and *F. culmorum,* respectively (Hudson, 2023). DON and NIV occur in 70% of barley samples in Brazil, while DON and ZEA in Tunisia (Jedidi *et al*., 2021; Krnjaja *et al*., 2024).

Oats: This crop is especially prone to infection with *F. langsethiae*, which produces type A T-2, HT-2 toxins. These toxins tend to be more common in temperate zones, such as the UK and Scandinavian countries. However, previous studies conducted using visible and near-infrared (Vis-NIR) spectroscopy demonstrated an accuracy up to 93% in identifying contaminated grains above the EU thresholds (Teixido-Orries *et al*., 2025).

Comparative perspectives

Globally, maize and wheat are the most mycotoxins contaminated grains in the world, as far as rice and barley come the second and third, while oats becoming more susceptible to T-2 and HT-2 toxins (Grenier and Applegate, 2013; Portell *et al*., 2020; Gachara *et al*., 2024; Teixido-Orries *et al*., 2025). Climatic conditions, practice of crop rotation, and storage environment play critical roles in deriving these patterns of contamination (Arata *et al*., 2024). Remarkably, the fungal ecological and toxin disparities among crops highlight the necessity for ecologically specific mitigation methods, debated in the subsequent passages with the accent on advanced measures of control and prevention. Climate, crop rotation, and storage continue to play an important role in defining the levels of mycotoxins contamination as presented in Table 2 and Figure 2.

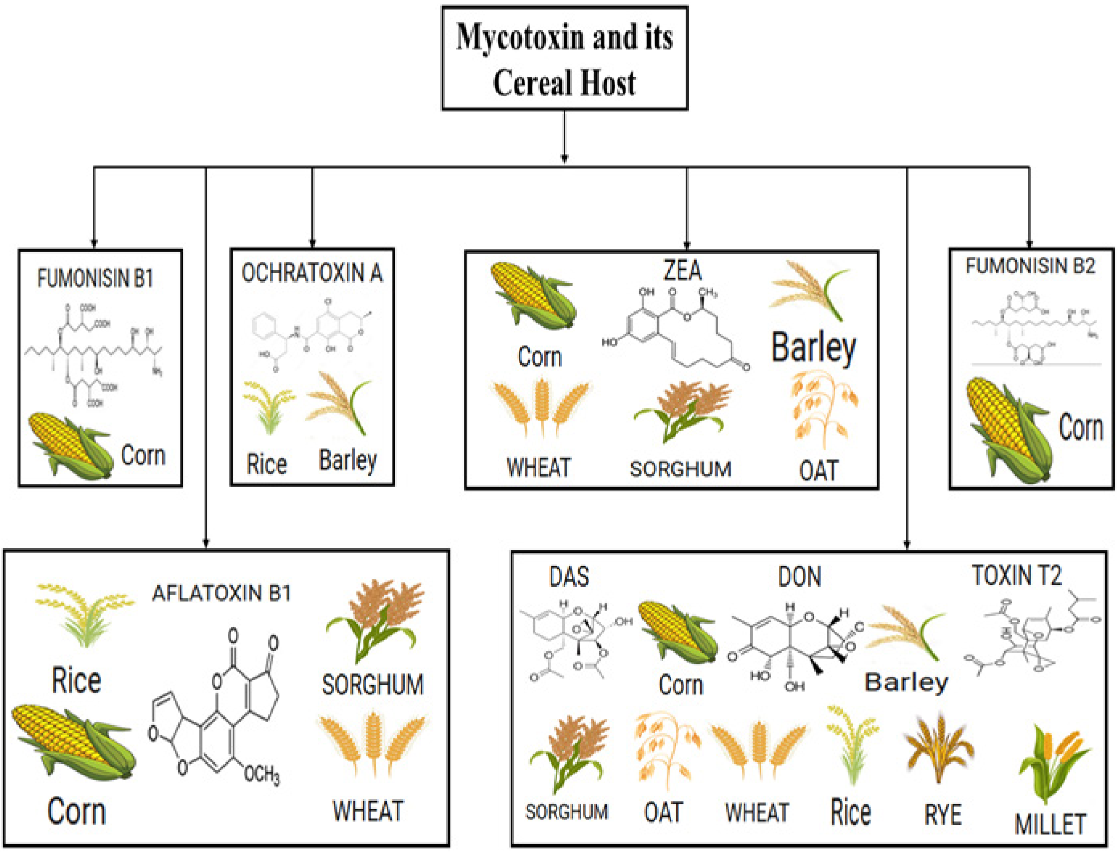

Figure 2: *Major mycotoxins produced by toxigenic fungi including: AF, OTA, FB, DON, ZEN, and T-2 toxin are toxic fungal metabolites that contaminate most cereals such as maize, wheat, barley, oats, rice, and sorghum. Each toxin is linked to a specific fungus (i.e., Aspergillus, Fusarium, and Penicillium) and causes severe health effects ranging from cancer and kidney damage to reproductive disorders and immune suppression.*

Table 2: *Comparative overview of major toxigenic fungi and their mycotoxins in cereal systems.*

Cereal crop	Predominant fungal genera/ species	Principal mycotoxins	Environmental & agronomic drivers	Major findings / Geographic evidence	Health and economic implications	Mitigation / control approaches
Wheat	*F. graminearum*, and *F. culmorum*	DON, ZEA, and NIV	High humidity and rainfall during anthesis, delayed harvest, and poor storage	*F. graminearum* dominates in humid zones, DON prevalent in wheat of Europe and Egypt, and trichothecene accumulation linked to rainfall (Portell 2020; Pastuszak 2021)	FHB disease, yield loss, and T-2 and HT-2 toxicity in humans and livestock	Crop rotation, resistant varieties, fungicide application, and humidity control
Maize	*F. verticillioides*, *F. proliferatum*, and *A. flavus*	FB_1, FB_2, and AFB_1, AFB_2	Warm, dry climate, drought stress, delayed drying, and storage	Highest mycotoxin prevalence globally, and co-contamination is common in Africa, Mediterranean, and Asia (Gachara 2024; Arata, 2024)	Liver cancer, neural tube defects, feed contamination, and trade losses	Rapid drying to <13% moisture, resistant hybrids, and improved storage and transport
Rice	*F. proliferatum*, *F. asiaticum*, and *A. flavus*	ZEA, DON, FBs, OTA, and Beauvericin	High post-harvest humidity, temperature >30 ˚C, and poor ventilation	*Fusarium spp.* dominates during harvest, *A. flavus* post-harvest, and high DON and ZEA in Southeast Asia (Phan 2021; Qiu 2024)	Aflatoxins and OTA exposure *via* rice products, and food safety concern in humid climates	Controlled drying, aerated storage, and regular mycotoxin testing
Barley	*F. graminearum*, *F. culmorum*, and *P. verrucosum*	DON, NIV, and OTA	Cool and wet conditions, and storage at high relative humidity (RH)	DON and NIV detected in >70% of samples in South America, and OTA in stored barley in North Africa (Hudson 2023; Jedidi 2021)	Reduced malt quality, feed contamination, and OTA nephrotoxicity	Timely harvest, storage aeration, and antifungal treatments
Oats	*F. langsethiae*, and *F. avenaceum*	T-2 and HT-2 toxins	Cool, humid climates, and poor drying efficiency	Prevalent in northern Europe, Vis–NIR spectroscopy detects contamination with >90% accuracy (Teixido-Orries 2025)	Trichothecene exposure risk in humans and livestock, and economic loss in oat trade	Rapid drying, optical sorting, resistant cultivars, and routine toxin monitoring

Where; This table summarizes the crop-specific fungal genera, mycotoxins, and factors associated with the environment/field related to wheat, maize, rice, barley, and oats (2013-2025) in various regions.

Environmental and storage factors influencing fungal infection and mycotoxins production

Fungal growth and mycotoxins accumulation in grains are strongly influenced by agricultural practices and storage conditions. Globally, high-humidity climatic conditions promote the growth of *Fusarium*, *Aspergillus*, and *Penicillium* species (Shabana *et al.*, 2022).

Environmental and climatic factors

The ecological factors that are important as determinants of fungal colonization and mycotoxins production in cereals are temperature, relative humidity, and rainfall. *Aspergillus* species that produce aflatoxins thrive better in high temperatures (33 to 38˚C) and relative humidity greater than 85%, while *Fusarium* species grow mainly in cooler and wetter environments. During the pre-harvest season, anthesis in the face of drought stress may also augment *Fusarium* infection and cause rise in T-2 production within diverse rainfall regimes (Awuchi *et al.*, 2021). Kinetic and probabilistic predictive modeling has shown that temperature and water activity work together to affect the growth rate of *A. parasiticus* and its AFB_1 yield in stored paddy (Pei *et al.*, 2021).

Crop management practices and agronomic practices

Fungal infection and mycotoxins contamination of cereal crops are highly affected by the agronomic practices. The benefits of intensive tillage have been linked to the rise of *Fusarium* infection and rise in DON concentrations, attributable to the increase in moisture in the soil and a decrease in the earthworm activity (Borràs *et al.*, 2022). Conversely, reduced tillage, crop rotation, and harvesting at the right time are conservation activities that can remarkably reduce the risk of mycotoxins contamination. Unfavorable weather conditions and changes of pathogen dominance have the potential to facilitate co-contamination of the spring wheat with DON, ZEA, and T-2 toxin (Kochiieru *et al.*, 2021). Another study using agronomic models has also demonstrated

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that flowering, soil management, and pest pressure are the main factors that determine pre-harvest AFs contamination, especially in maize (Focker *et al.*, 2023).

Post-harvest and storage conditions

Post-harvest handling highly influences mycotoxins production. In the Central Highlands region of Vietnam, conventional post-harvest handling practices such as delayed drying, in-field shelling, and storage in ground pits promote the growth of *F. verticillioides*, leading to FB contamination (Tran *et al.*, 2021). Improved handling practices such as off-field shelling and drying in cement yards considerably suppress fungal concentrations. Comparable results have been obtained in Ethiopia, wherein poor storage and lack of sorting remarkably increased the concentration of FB_1 in maize, exceeding the permissible levels set by the World Health Organization (WHO) (Mohammed *et al.*, 2022).

Predictive and biological insights

Integrative approaches involving both environmental modeling and microbial community analyses have made it possible to effectively predict levels of fungal contamination risk. On the other hand, a large-scale study involving wheat samples from 12 provinces in China has been able to demonstrate the accuracy of DON levels predicted by *Fusarium* detection, along with other environmental factors, with more than 90% accuracy by random forest models (Qi *et al.*, 2024). On the whole, the synergistic combination of climatic factors, agricultural practice, and storage practice determines the landscape of mycotoxins risk. Adaptive managements, including climate forecasting, resistant varieties, and optimal drying and storage methods are therefore critical to ensure the sustainability of safe crop production chains in cereal growing areas (Tran *et al.*, 2021; Shabana *et al.*, 2022). Predictive models of mycotoxins contamination are a crucial tool for managing the impact of climate change on food safety. These models integrate climate data with crop phenology and fungal biology to forecast mycotoxin's levels, allowing for targeted management and adaptation strategies (Awuchi *et al.*, 2021; Focker *et al.*, 2023).

Types of nanomaterials used in fungal and mycotoxins management

Silver (Ag), ZnO, CuO, TiO_2, and Fe_2O_3 are examples of metal and metal oxide NPs that exhibit strong antifungal and antimycotoxigenic effects and are increasingly being explored for protection of cereal crops (Maity *et al.*, 2022). Their effectiveness arises from shared nanoscale characteristics such as small particle size, a large surface-to-volume ratio, and generation of ROS, all of which interfere with fungal growth and mycotoxins production (Nabi *et al.*, 2024). These common mechanisms make metal-based NPs functionally versatile candidates and potentially cost-effective alternatives to traditional chemical fungicides (Gacem and Abd-Elsalam, 2022).

Silver nanoparticles (AgNPs)

Silver nanoparticles (AgNPs) are among the most widely studied antifungal nanomaterials and consistently have demonstrated broad-spectrum activity against *Aspergillus*, *Penicillium*, *Candida*, and *Fusarium* species. Their efficacy is strongly size-dependent, with smaller particles generating higher levels of ROS that damage fungal membranes and intracellular components (Mansoor *et al.*, 2021). AgNPs also suppress mycotoxins biosynthesis, including reductions in AFB_1 production in maize, and remain effective even against fungicide-resistant strains such as *F. graminearum* (Jian *et al.*, 2022; Hussein and Owied, 2024). Both chemically synthesized and plant extract-mediated AgNPs have demonstrated consistent antifungal performance across multiple cereal-associated pathogens (Nguyen *et al.*, 2020; Firdous *et al.*, 2024).

Zinc oxide nanoparticles (ZnO NPs)

Zinc oxide NPs (ZnO NPs) have good optical and photocatalytic characteristics that increase their antifungal and anti-mycotoxigenic properties (Kalia *et al.*, 2020). Green synthesized ZnO NPs are often more active than chemically produced counterparts (Mohammed *et al.*, 2018). As an illustration, 100 µg/g ZnO NPs lowered *A. flavus* attacks in maize from 67% to 30% and lowered AFs concentrations from 45 ng/g to 14 ng/g (Hernández-Meléndez *et al.*, 2018). Synthesized ZnO NPs from *Syzygium aromaticum* have induced oxidative stress and disturbed the ergosterol synthesis in *F. graminearum*, remarkably reducing the production of mycotoxins (Lakshmeesha *et al.*, 2019).

Copper-oxide and copper nanoparticles

Copper-based nanomaterials are highly reactive and possess strong redox potential, underlying their pronounced antifungal activity. Biosynthesized copper NPs (CuNPs) completely inhibited *F. oxysporum* and *Phytophthora capsici* at relatively low dosages, whereas larger CuNPs (20–50 nm) reduced *F. oxysporum* growth by more than 90% at higher concentrations (Viet *et al*., 2016; Pham *et al*., 2019). Compared to AgNPs, CuNPs generally require higher concentrations to achieve comparable antifungal efficacy, but offer advantages in terms of cost and compatibility with integrated pest-management systems. CuNPs have also exhibited higher redox-driven activity than ZnO NPs; however, they may suffer from stability limitations due to oxidation to copper (I) oxide (Cu_2O), copper(II) oxide (CuO), or copper hydroxide [$Cu(OH)_2$], which may influence their persistence and toxicity profiles (Thipe *et al*., 2022; Mateo *et al*., 2025).

Nanoparticles of titanium dioxide (TiO2 NPs)

Sol-gel, co-precipitate, or green routes produced TiO_2 NPs have shown to display antifungal and mycotoxins-reduction properties (Al-Saji and Al- Nazzal, 2021; Olayil *et al*., 2022). TiO_2 NPs with a size of 70 nm at 80 µg/ml inhibited 95% of OCTA production. Pomegranate peel and *Trianthema portulacastrum* serve as sustainable green sources for synthesizing TiO_2 NPs, which could be successfully used as a sustainable source of these NPs against *Colletotrichum graminicola* and *Ustilago tritici* (Alabdallah *et al*., 2023; Nabi *et al*., 2024).

Nanoparticles of magnetite (Fe2O3 NPs)

Fe_2O_3 NPs (approximately 5 nm) have been effective in controlling *F. oxysporum*, reducing disease symptoms and triggering plant defense mechanisms (Kong *et al*., 2025). Fe_2O_3NPs (40 mg/ L) coated with humic acid (Fe_2O_3/HA NPs) have enhanced yield and plant defense enzymes without exhibiting toxicity (El-Ganainy *et al*., 2022). Additionally, Fe-based NPs synthesized using spinach or coffee extracts considerably inhibited *T. roseum* and *P. chrysogenum* (Parveen *et al*., 2018; Ashraf *et al*., 2022). Fe_2O_3NPs have moderate antifungal activity, higher biocompatibility, and plant defense induction, and therefore, can be considered especially effective in the context of sustainable cereal protection approaches (Mateo *et al*., 2025).

Biopolymer-based nanocarriers

Biopolymer-based nanocarriers (e.g. chitosan, alginate, starch, and cellulose nanocomposites) provide eco-friendly platforms or antifungal and anti-mycotoxigenic delivery. These systems are biocompatible, biodegradable, and have controlled-release capacity, making them applicable in the strategies of safe cereals protection (El-Araby *et al*., 2024).

Chitosan nanoparticles (CNPs)

Chitosan nanoparticles (CNPs) created by ionic gelation usually have stable spherical mesoparticle structures and preferential biocompatibility. Their safety profiles have been shown to be good in cytotoxicity tests, since they are non-toxic at a concentration of 500 µg/mL and can be used as a carrier of plant-derived bioactive compounds, explaining why they are suitable in antifungal practices (Mhlongo, 2013). Shrimp-head-derived chitosan has produced fungistatic activity against *A. parasiticus*, preventing mycelial growth, germination of spores, and production of AFB_1 at IC_{50} levels of 6.71 and 10.66 g/L (Cota-Arriola *et al*., 2011).

Functional and loaded CNPs

Entrapment of *L. rhamnosus* bioactive compounds in CNPs has yielded natural antifungal agents, inhibiting 89.4% of *A. flavus* aflatoxins production in maize at 7 mg/mL concentration (Abdel-Nasser *et al*., 2025).

Composite and hybrid systems

Chitosan NP composites can maximize antifungal activities because chitosan is biocompatible, and inorganic nanomaterials may expound their activity in this area. The CS/ZnO nanocomposites have inhibited the growth of *Aspergillus* spp. and AFB_1 production (Asghar *et al*., 2025), and the hybrids of Cu–chitosan have suppressed the expression of *aflR* with lower metal toxicity (Hassan *et al*., 2022). Collectively, the hybrid systems have yielded a higher stability, better antimicrobial properties, and less toxicity compared to their constituent parts, and herein lies the importance of composite architecture in nanotechnology-based fungicides.

Starch and cellulose nanocomposite films

Starch-based films containing biosynthesized Ag, ZnO, TiO_2 NPs, and cold plasma treatment along with carboxymethyl cellulose/polyvinyl alcohol/nanoclay (CMC/PVA/nanoclay) films have successfully reduced the contamination by *A. terreus* and *A. flavus* in maize and wheat flour, respectively, displaying their efficacy in combination, along with retaining gluten and starch levels (Yisa, 2023; Amini *et al*., 2024).

Sustainability perspective

Green NPs, especially Ag, ZnO, TiO_2, and iron oxides have been observed as ecologically safer antifungal agents with multifaceted properties, including adsorption, antioxidant properties, and UV-light-induced photocatalysis (Gelaye and Luo, 2025). Green nanotechnology aims to achieve sustainability in terms of reduced environmental risks with retained potency (Vurro *et al*., 2019). Thus, biopolymeric NPs represent a promising means of achieving sustainable antifungal treatment and protecting against mycotoxins contamination in cereal crops.

Green-synthesized nanoparticles from plants and microorganisms

Green synthesis involves the utilization of biological resources, such as plant extracts, algae, fungi, and bacteria, as reducing and stabilizing factors in the production of nanomaterials in an eco-friendly manner. Electrons are donated to the metal ions by phytochemical constituents, forming NPs without using dangerous reagents (Shafey, 2020; Soltys *et al*., 2021). This method has the benefits of low toxicity, energy consumption, and low-cost relative to the traditional chemical synthesis (Anand *et al*., 2022). Green nanotechnology greatly reduces potential adverse effects on the environment and community health, offering an eco-friendly alternative for managing plant pathogens (Bahrulolum *et al*., 2021).

Plant-mediated nanoparticles

Plant-mediated NPs consistently demonstrate strong antifungal and anti-mycotoxigenic properties across multiple studies. Green-synthesized metal and metal-oxide NPs such as cerium oxide, Ag, Se, and ZnO effectively suppress fungal growth and, in many cases, reduce associated mycotoxins in cereals and other crops (Pillai *et al*., 2020; Alotaibi *et al*., 2023; Qureshi *et al*., 2023; Badmos *et al*., 2025; Hussein *et al*., 2025). These plant-derived systems provide eco-friendly, biocompatible alternatives that inhibit pathogenic fungi and limit mycotoxins production, supporting their potential in sustainable crop protection strategies (Melkamu and Bitew, 2021).

Microbial-mediated nanoparticles

Microbial-mediated NPs synthesis is a relatively emerging but relatively underutilized area of green nanotechnology. Bacteria and cyanobacteria fungi are also good reducing and stabilizing agents because of their tolerance to metals bioaccumulation ability and internal metal ions processing, allowing the size and morphology of NPs to be controlled. Fungi in specific also serve as scalable nanofactories (Khan *et al*., 2017). Examples are AgNPs synthesized by *Spirulina platensis* or *Moringa oleifera* extracts, which depicted good antifungal activity against *A parasiticus*, with *S. platensis* being more effective because it has a high concentration of phenolics (Yassein *et al*., 2025).

Comparative perspectives

Green-synthesized NPs have antifungal combination effects, including induction of oxidative stress, cell membrane destabilization and blockage of mycotoxins synthesis (Alotaibi *et al*., 2023; Qureshi *et al*., 2023). Plant-based synthesis pathways can be produced in large quantities extremely quickly and are amenable to high-scale production, but can be unable to produce homogenous phytochemical composition, resulting in poor reproducibility between batches (Shafey, 2020; Soltys *et al*., 2021). Conversely, microbial synthesis provides a greater degree of control over NPs size and morphology and offers more reproducible production conditions, but generally is not scalable and may face increased regulatory scrutiny because of biosafety issues (Bahrulolum *et al*., 2021; Yassein *et al*., 2025). These biosynthetic solutions can be used together to promote sustainable nanotechnology of cereal protection and improve food safety.

Lipid- and protein-based nanoformulations

Nanocarriers made of lipids and proteins are biocompatible platforms having the potential to entrap bioactive antifungal compounds to increase their stability and targeted delivery. These nanosystems shield delicate actives and enhance solubility, and provide food-grade strategies to manage mycotoxins, showing promise in controlling mycotoxins production (Krumova *et al*., 2024).

Lipid-based systems

Lipid nanocarriers, such as nanoemulsions, solid lipid NPs (SLNPs), liposomes, and nanostructured lipid carriers are natural lipids mixed with surfactants to create colloidal suspension and prevent fungal growth in agricultural and food matrices (Mashaghi *et al*., 2013). They can be particularly used in controlled-release applications due to their inherent biocompatibility and capability to entrap both hydrophilic and lipophilic molecules (Jin *et al*., 2019). Indicatively, the essential oil of tea-tree (*Melaleuca alternifolia*) added to solid liposomes has turned out to be a complete inhibitor of *Monilinia fructicola*, the pathogen of brown rot (Xu *et al*., 2022).

Liposomes: Liposomes are the first and most studied lipid nanocarriers. These are self-assembled amphiphilic phospholipid bilayers which entrap active molecules in aqueous or lipidic compartments. Such two loading provides an opportunity to deliver various antifungal agents with a low level of toxicity (Guimarães *et al*., 2021). Phosphatidylcholine and oleic acid liposomes containing garlic extract have exhibited high antimycosis activity, high entrapment and inference, thermal stability, and ability to inhibit molds growth in the wheat bread for up to five days (Pinilla *et al*., 2019). A novel approach to food safety and public health protection may be provided by the Carotenoid-Loaded Nanostructured Lipid Carriers, showing promise in enhancing their protective effects against OTA toxicity (Pinna *et al*., 2024). The stability of fludioxonil-loaded liposomes, including Nano-PEGylated and cationic liposomes is high with sustained release and *Botrytis cinerea* inhibition, and therefore, these liposomes have potential to be used in controlling fungal infection in cereal crops (Agnusdei *et al*., 2024).

Protein-based nanoparticles: Gelatin, soy, and zein are renewable and biodegradable proteins that can be used in the fabrication of NPs (Kumar and Lal, 2014; Tarhini *et al*., 2017). Plant proteins are especially appreciated in terms of safety and versatility. They have numerous reactive groups allowing them to be surface modified by conjugation with carbohydrates or ligands to enhance targeting and stability (Hong *et al*., 2020; Kianfar, 2021). A recent research has proved that zein and gelatin NPs are effective to encapsulate phenolic and enzymatic bioactives and improve antifungal and antioxidant activity in cereals (Oliveira-Pinto *et al*., 2024). Small peptides, resembling proteins, can mimic the catalytic sites of natural enzymes to generate synthetic enzymes with lyase, hydrolase and oxidoreductase activities. This approach offers a promising strategy for mycotoxins degradation, supported by their structural diversity, excellent biocompatibility, and well-established synthesis protocols (Zhao *et al*., 2022; Fang *et al*., 2025).

Comparative insight: Lipid-based formulations are very good at delivering vulnerable or hydrophobic antifungal agents (Jin *et al*., 2019; Xu *et al*., 2022; Agnusdei *et al*., 2024), while the protein NPs offer tunable surface chemistry and low toxicity (Oliveira-Pinto *et al*., 2024). Combination of these biopolymeric nanosystems may facilitate the shift towards environmental sustainability and food safety, supporting the move towards greener antifungal technologies (Guimarães *et al*., 2021; Krumova *et al*., 2024).

Hybrid and smart nanocomposites

Hybrid nanocomposites combining organic inorganic and biological components provide multifunctional synergistic antimicrobial adsorptive and photocatalytic activity, offering potential solutions for fungal pathogens and cereal mycotoxins reduction (Ngwenya *et al*., 2025; Paek *et al*., 2011).

Graphene-based hybrids: Hybrids of graphene oxide exhibit multifunctional antifungal activity due to their synergistic antimicrobial, antibiofilm, and photocatalytic properties. For example, reduced graphene oxide combined with NiO has demonstrated strong UV-activated antifungal effects, causing severe cellular deformation in *Candida* and *Aspergillus* species (Elbasuney *et al*., 2021). Likewise, green-synthesized ZnO, CuO, graphene hybrids have inhibited *A. flavus* and reduced AFB_1–associated phytotoxicity, enhancing fungicidal performance and promoting seeds growth (Ngwenya *et al*., 2025).

Polymer–metal hybrids: Bacillus-derived MgO NPs (2960 nm) used in the synthesis of chitosan magnesium (CSM) nanocomposites demonstrated a high degree of antimicrobial activity against *Acidovorax oryzae* and *Rhizoctonia solani*, and the nanostructure has been verified by ultraviolet–visible spectroscopy (UV–Vis), Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) analyses (Ahmed *et al*., 2021). Chitosan based hybrids such as CS -ZnO, CS –CuO, and CS -SiO 2 have had better antifungal activity against *F. solani* and *Alternaria solani* compared to nystatin. Their small size (60170 nm) and cationic surfaces are beneficial in disruption of membranes and production of oxidative stress (Krumova *et al*., 2024).

Magnetic graphene and adsorptive composites: Graphene oxide (GO) has considerably inhibited *Bipolaris sorokiniana in vitro* and *in vivo*, and decreased crop infection, whereas GO -FeO nanocomposites have reduced the severity of downy mildew (Zhang *et al*., 2022). Graphene oxide–silver nanoparticles (GO-AgNPs) are antifungals possessing a high affinity against *F. graminearum*, reducing leaf spot symptoms and displaying synergetic antimicrobial efficacy, three folds stronger than AgNPs and seven folds higher than GO (Chen *et al*., 2016). According to Horky *et al*. (2018), magnetic graphene is an inexpensive mycotoxins adsorbent that binds mycotoxins to facilitate magically easy removal. Control of mycotoxins through nanotechnology encompasses fungal suppression, mycotoxins adsorption, and toxicity reduction by employing NP technologies Horky *et al*. (2018). The integration of mechanical strength, catalytic reactivity, and biocompatibility is brought together by hybrid and smart nanocomposites (Abd-Elsalam, 2024). Combining various functional stages, allows dual or triple activities, such as antifungal, detoxification, and self-regeneration. These witnessed characteristics thereby place the nanoformulations as the next generation technologies in sustainable reduction of mycotoxins (Abd-Elsalam, 2024; Samson Prince *et al*., 2025). Nevertheless, these inventions will have to be converted into realistic cereals production systems and will demand strategic elimination of challenges linked to regulatory approval, large scale production, and sustenance of regular performance in field conditions (Sharma *et al*., 2024) (Figure 3).

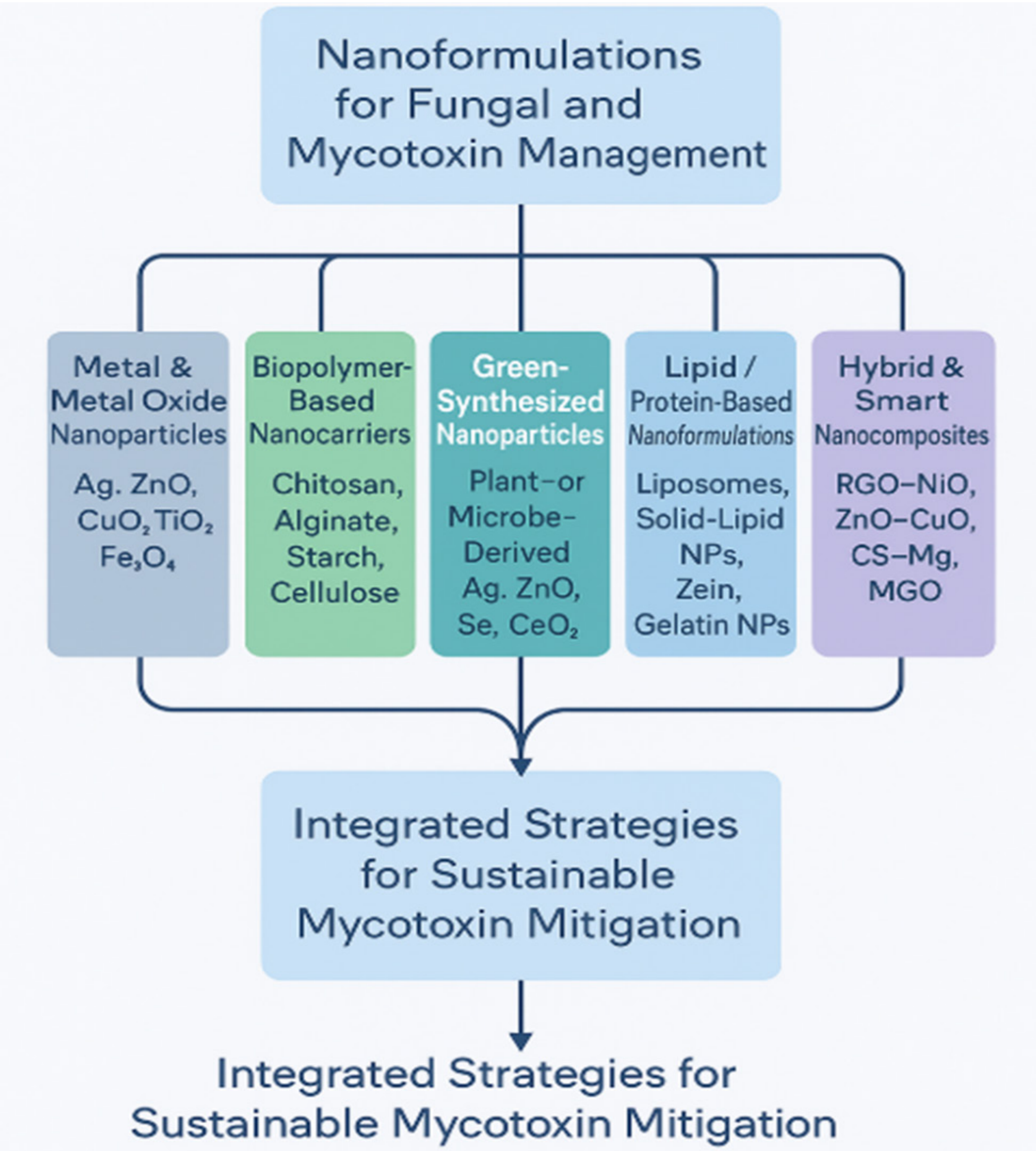

Figure 3: *Hierarchical nanoformulations classification to control fungi and their associated mycotoxins production.*

Mechanisms of antifungal and antimycotoxigenic action

Disruption of fungal cell wall and membrane integrity

The antifungal effects of nanomaterials are through direct contact to the cell wall, interfering with the electrostatic and structural stability of the fungal cell wall, penetrating the chitin-glucan matrix, and damaging the plasma membrane, leading to loss of integrity, intracellular leakage, and fungal cell death (Lakshmeesha *et al*., 2019; Macías-Rubalcava *et al*., 2025). When in contact, NPs like AgNPs and ZnO NPs interact with membrane lipids and proteins resulting in depolarization and high permeability. Such an interaction interferes with the distribution of ergosterol; a major sterol needed to sustain the integrity of fungal membranes, and causes the leakage of important cellular organelles such as ions, amino acids, and nucleotides (Krumova *et al*., 2024). The presence of such membrane perturbations has been confirmed in *A. flavus* and *F. oxysporum* by scanning and TEM, which have shown wrinkled, ruptured, and collapsed hyphal structures (Anumudu *et al*., 2024). There are also considerable membrane-disruptive effects of biopolymeric NPs, especially of chitosan-based systems (Lakshmeesha *et al*., 2019).

Reactive oxygen species generation and oxidative stress

As fungicide substitutes, biopolymers, for instance, have unique qualities making them sustainable: they are non-toxic, biodegradable, and derived from renewable sources (Sharma *et al*., 2024). Moreover, they can directly inhibit fungal growth, stimulate the plant immune system (elicitors), or act as carriers for controlled release of active ingredients. Their use frequently involves nanoformulations for increased efficacy and decreased environmental impact, making them eco-friendly and effective for plant protection (Yang *et al*., 2023).

During the interaction between fungal cells with NPs, redox reactions on the surface and in the cytoplasm cause the appearance of highly active species, superoxide anion (O^{-2}), hydroxyl radical ($^{\bullet}OH$), and hydrogen peroxide (H_2O_2). These molecules impair redox homeostasis, leading to lipid, protein, and nucleic acid degradation and increase of oxidative damage (Slavin and Bach, 2022; Yang *et al*., 2023). Metallic NPs, especially Ag, ZnO, CuO, and TiO_2 have a high ROS-generating potential. AgNPs mediate the reaction of dissolved oxygen into ROS by transferring electrons between Ag^+ ions to react with cell constituents. Conversely, ZnO NPs cause oxidative stress through photochemical excitation and ionic dissolution releasing Zn^2+ ions that accelerate the intracellular accumulation of ROS (Shankar *et al*., 2024). TiO_2 NPs also increase oxidative reactions under a light source, producing electron-hole pairs that react with oxygen and water to produce radicals of the free $^{\bullet}OH$ radicals, which may oxidize fungus membranes and organelles (Rana *et al*., 2024). The resultant oxidative stress causes cell membrane lipid peroxidation, enzyme and structural protein oxidation, and DNA fragmentation, leading to cell death. Fluorescence measurements of 2′,7′-dichlorofluorescein diacetate (DCFH-DA) are used to ascertain a sharp rise in the ROS fluorescence intensity after the addition of Ag and ZnO NPs in *A. flavus* and *F. graminearum* (Krumova *et al*., 2024).

Conclusively, the generation of ROS caused by NPs is a dual process directing fungal tissues to oxidative processes and indirectly preventing the synthesis of mycotoxins by modifying the redox signaling of the cells.

Inhibition of spore germination and hyphal growth

Another substantial mode of nanomaterials antifungal action is through the inhibition of fungal growth and germination of spores. Spores are very resistant propagules that trigger the fungal colonization under favorable conditions. This process is interrupted by NPs, which adsorb onto the surface of spores, hamper nutrients uptake, and cause oxidative and ionic stress that inhibits the emergence of propagule germ tube (Slavin and Bach, 2022). Metal-based NPs such as Ag, ZnO, and CuO) inhibit fungal growth by disrupting membrane integrity, releasing metal ions, and interfering with ions transport. These mechanisms collectively prevent spore germination and the formation of germ tubes. Notably, AgNPs have exhibited potent antifungal activity against *Fusarium* and *Aspergillus* spp. (Anumudu *et al*., 2024). Similarly, ZnO NPs have prevented conidial germination of *P. expansum* up to 80% by causing oxidative damage and disrupting mitochondrial activity (Wang *et al*., 2024).

Nanoparticles of biopolymers, especially chitosan-based systems, also prevent the germination of spores and form a film of polymer covering the spores, preventing movements of gases and nutrients. The amino groups in chitosan are positively charged, which interact with negatively charged walls of the fungal spores through electrostatic forces, preventing swelling and appearance of the germ tube (Lakshmeesha *et al*., 2019). In addition to inhibiting spore germination, nanomaterials suppress mycelial elongation and branching. Metal and hybrid NPs interfere with cytoskeletal organization and microtubule-based systems that mediate directional growth; thus, hyphal extension is impaired (Krumova *et al*., 2024). The outcomes of the NPs action are the shortening, irregularity or even swelling of hyphae with lower sporulation capacity. Together, the inhibition of spore germination and elongation of hyphae by NPs interferes with the initial establishment of fungi, which does not allow colonization and subsequent production of mycotoxins in stored or field crops.

Modulation of mycotoxins biosynthetic pathways

Besides its structural and oxidative processes, nanomaterials can directly disrupt the biosynthetic pathways of mycotoxins production (Jobe and Mwanza, 2025). The fungal biosynthetic gene clusters (BGCs) *afl*, *TRI* and *FUM* encode pathways for mycotoxins production (*i.e*., AFs, T-2, and FBs) (Liew *et al*., 2023). These gene clusters are arranged as gene families for coordinated mycotoxins production, enabling pathway-level inhibition rather than targeting individual genes, disrupting the entire mycotoxins production process through common regulators or cluster-wide epigenetic control (Gacek and Strauss, 2012), providing broad-spectrum antifungals or disease biocontrol.

The biosynthetic pathways for mycotoxins are regulated through NPs; mainly by redox mediated signaling and transcriptional regulation (Zhao *et al*., 2017). Oxidative stress caused by the metal and metal oxide NPs alters the redox balance within the cell, subsequently influencing the transcription factors that regulate biosynthesis of mycotoxins (Zhao *et al*., 2017; Gjorgieva-Ackova *et al*., 2025). In one example, the high concentration of ROS decreases the expression of the aflatoxin cluster regulatory genes, including *aflR* and *aflS*, and subsequent down-regulating the downstream enzymes, including O-methyltransferase and versicolorin desaturase (Zhao *et al*., 2017; Yang *et al*., 2023). AgNPs and ZnO NPs have been reported to silence *TRI5* and *TRI6* expression in *F. graminearum*, therefore, inhibiting the synthesis of trichothecenes (Perochon and Doohan 2024). On the same note, *FUM1* and *FUM13* genes become downregulated when TiO_2 and CuO NPs are applied in *F. verticillioides*, resulting in reduced FB_1 concentrations (Anumudu *et al*., 2024).

Chitosan-based nanocomposites interfere with the production of mycotoxins mainly by blocking the binding of indispensable metal cofactors, in particular, Mg^2+ and Zn^2+, disrupting the normal functioning of critical enzymatic pathways necessary for production of mycotoxins (Lakshmeesha *et al*., 2019). Transcriptomic and metabolomic data have validates the fact that NPs treatment causes globalization of secondary metabolism, where cell resources are reallocated to repair and stress-response pathways in place of mycotoxins production (Anumudu *et al*., 2024). Therefore, nanomaterials have a strong control over the metabolism of fungi as the mycotoxins in treated cultures have decreased considerably up to 90% of aflatoxin B1 and 75% of DON in several previous studies. All these results presented in this review suggest that nanomaterials are effective not only as physical and chemical antifungal agents, but also as molecular sources that inhibit the expression of biosynthetic genes and metabolic flux of mycotoxins, which are useful in food safety and growth control of fungi.

Synergistic effects of nanomaterials with natural antifungal compounds or conventional fungicides

Hybrid nanomaterials are composites combined with metals and organic molecules, and have synergistic properties that can be used to increase antifungal efficacy (Alghuthaymi *et al*., 2021). The synergistic effect between the nanomaterials with other antifungal agents, such as natural bio-actives or chemical agents is a potential approach in increasing efficacy and reducing environmental and toxicological effects. Carriers NPs can be used as carriers, stabilizers, or catalytic enhancers that enhance the biological performance of companion molecules through increasing their solubility, degradation protection, and release control (Yassin *et al*., 2025).

Synergy with natural antifungal compounds. Integrating nanomaterials with the plant-based compounds, including essential oils, polyphenols, and organic acids, may increase antifungal efficacy to a large degree (Davidova *et al*., 2024). AgNPs and clove essential oil provide a remarkable increase in the inhibition of *A. flavus* and *P. expansum* at a much lower concentration than either of the individual agents (Bouqellah *et al*., 2025). This enhanced functionality is consistent with a bigger trend based on the fact that nano-based delivery systems enhance membrane permeability and deeper permeation of volatile bio-actives, and extend the antifungal activity. Similar synergistic impacts have been also reported of other plant based compounds used in chitosan based nanocomposites, stabilizing the bio-actives, decrease volatility, and strengthen interactions with the negatively charged fungal cell walls (Lakshmeesha *et al*., 2019).

Metal and metal oxide NPs have the potential to complement the synthetic fungicides with respect to their modes of action. As an example, ZnO or CuO NPs combined with triazole fungicides (*i.e*., tebuconazole, difenoconazole) have been more effective in inhibiting *F. graminearum* and *A. niger* using half the dose of conventional fungicides (Ilkhechi *et al*., 2021). In maize, case studies have revealed that nano-enabled fungicides and storage coatings reduce AFs and FBs contamination, and enhance kernel integrity during drying and storage. Nanoformulations based on chitosan and lipid at silk stage have lowered the frequency of ear-rot, while ZnO/Ag nanocomposites liners have stopped secondary invasion by fungi during storage (Alkuwari *et al*., 2022). NPs enhance the penetration of fungicides and generate a second effect of oxidative stress, both cause cellular destruction of fungal membrane and fungal metabolism (Jian *et al*., 2022). Fungicide resistance is also covered by this synergistic approach, as the combination of NPs with chemical agents acts on more than one site in the fungal cell, decreasing the chances of fungal adaptation. This combination of strategies offers general effectiveness, and reduces the amount of chemicals used and the amount of chemical residue in the environment (Malandrakis *et al*., 2022).

In summary, nanomaterial fungicide and nanomaterial-bioactive synergism provides a new and sustainable method of dealing with toxigenic fungi. Such systems combine physical, chemical, and biological antifungal approaches, offering foundations to the next-generation formulations, which can be more effective, less resistant, and safer in agricultural use.

Overview of antifungals and antimycotoxigenic activity mechanisms

Nanomaterials exert antifungal and antimycotoxigenic effects through an integrated and multi-target modes of action. Initial disruption of the fungal cell wall and plasma membrane is followed by ROS generation, leading to oxidative damage that inhibits colonization, nutrients uptake, hyphal growth, and spore germination. At the molecular level, NPs suppress key mycotoxins biosynthetic genes such as *aflR*, *TRI5* and *FUM1*, reducing mycotoxins production. In addition, nanomaterials enhance the efficacy of natural bio-actives and conventional fungicides through synergistic interactions. Collectively, these coordinated mechanisms position nanotechnology as a sustainable tool for managing fungal pathogens and their mycotoxins in agricultural systems (Mechanistic overview in Figure 4).

Cereals production and nanomaterials post-harvest system applications

Multiple studies conducted on food science have confirmed that NPs have outstanding barriers, mechanical characteristics, and excellent antifungal and self-cleaning functionality. Due to these unique properties and their extensive prospects for use in the sphere of food and agriculture, nanomaterials have been suggested and adopted extensively (Abdelhamid and Mahmoud, 2023; Ahmed *et al*., 2023).

Pre-harvest protection: Nano-enabled fungicides and biocontrol delivery

Post-harvest fungal infections further increase cereal yield losses, which is estimated to be 10–20% globally, attributed to the appreciable contributions by *Fusarium*, *Aspergillus*, and *Alternaria* spp. in rice, wheat, maize, and soybean (Steinberg and Gurr, 2020). Annual economic losses in the world amount to USD 60 billion due to resistant phytopathogens (Gai and Wang 2024). AFs poisoning, especially in maize, is a serious problem in areas that have a lack of appropriate storage facilities (Achugbu *et al*., 2022; Gachara *et al*., 2024).

Equally, a nanocrystalline cellulose–TiO_2 composite (GNC) derived from recycled cotton waste has shown exhibited synergistic antifungal activity between nanocrystalline cellulose and TiO_2 NPs against *F. graminearum* and *Phytophthora* spp. activities, suggesting that the nanomaterial can be used to develop a sustainable, environmentally friendly nanofungicide for pre-harvest crop protection (Sharma *et al*., 2025). *Colletotrichum gloeosporioides*, *P. steckii*, and *Cladosporium oxysporum* infections in fruit systems are greatly mitigated with the help of chitosan/nano-TiO_2 composite that has inhibited the growth of molds and enhanced protein and nucleic acid leakage, which is a symptom of membrane disruption (Xing *et al*., 2021).

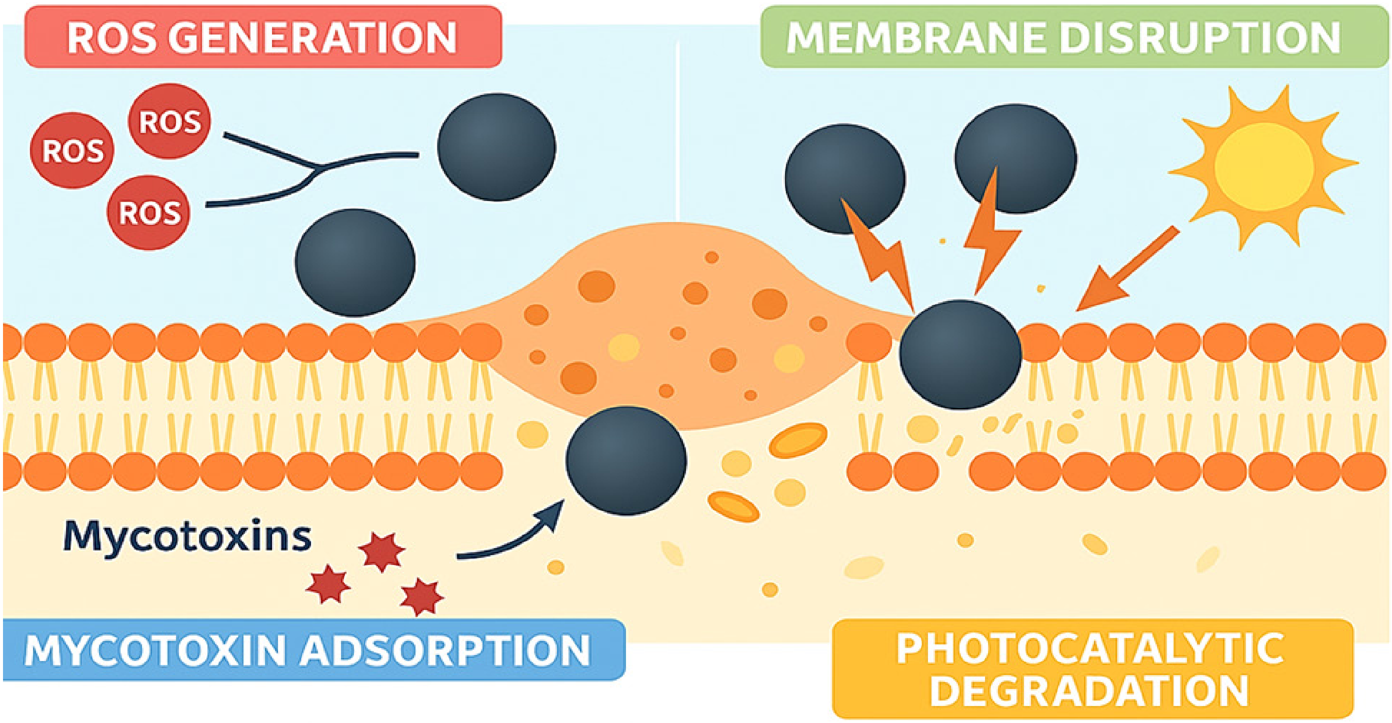

Figure 4: *Mechanistic overview of nanomaterials antifungal actions (created by Nano Banana AI).*

Integration of nanoformulations in packaging and coating materials

Nano-packaging technologies are gaining use to improve the shelf life and safety of food products based on cereals. Compared to traditional biopolymer films, the mechanical strength, water resistance, and thermal stability of barrier-enhancing nanocomposites are higher (biopolymer films reinforced with montmorillonite, ZnO, TiO_2, kaolinite, or AgNPs) (Chaudhary *et al.*, 2020). CMC/PVA/nanoclay (CPN) films modified with cold plasma also add to the barrier performance but maintain the intrinsic gluten and starch structure of wheat flour (Amini *et al.*, 2024). Antifungal and active-packaging nanomaterials further contribute to cereal preservation. Zein films loaded with pomegranate peel extract encapsulated in CNPs have demonstrated strong antioxidant and antimicrobial activity, particularly when surface-modified with cold plasma (Cui *et al.*, 2020). Starch/TiO_2 bio-nanocomposites improve hydrophobicity and reduce water vapor permeability, offering eco-friendly options for grain storage (Goudarzi *et al.*, 2017). Green-synthesized AgNPs embedded in microcrystalline cellulose films extend food shelf life by suppressing microbial degradation, where AgNPs grown on chitosan derived from wheat residues effectively inhibit *F. oxysporum* and *Aspergillus* spp. without phytotoxicity (Pandian *et al.*, 2023; Mondéjar-López *et al.*, 2023). Other findings have also associated the dynamics of fungal infection in stored cereals with the inoculum location, water activity, and respiration of fungi, proving that nanotechnology-based interventions have to target the storage micro-environment as well (Portell *et al.*, 2020). *C. gloeosporioides*, *P. steckii*, and *Cladosporium oxysporum* infections in fruit systems have been greatly mitigated with the help of chitosan/nano-TiO_2 composite that has inhibited the growth of molds and enhanced protein and nucleic acid leakage; a symptom of membrane disruption (Xing *et al.*, 2021).

Case studies in wheat, rice and maize

In wheat, Gluten-based nanocomposite films containing quercetin nanoliposomes and ZnO NPs have enhanced the mechanical strength, antioxidant activity, and antimicrobial activity against wheat-associated microorganisms, which proves to be promising in active packaging (Bakeshlou *et al.*, 2024). In rice, nano-encapsulated *B. amyloliquefaciens* D203 has shown promising results in enhancing the biocontrol of *Magnaporthe oryzae* (Qiu *et al.*, 2024), and increased the activation of antioxidants and defense enzymes in treated seedlings, demonstrating induced systemic resistance and reduced disease severity (Santos *et al.*, 2022). All these investigations confirm the effectiveness of nanoformulations in maintaining major cereals, with an enhanced deposition, persistence, and safety at low active-ingredient levels, compared to the traditional fungicides (Figure 5).

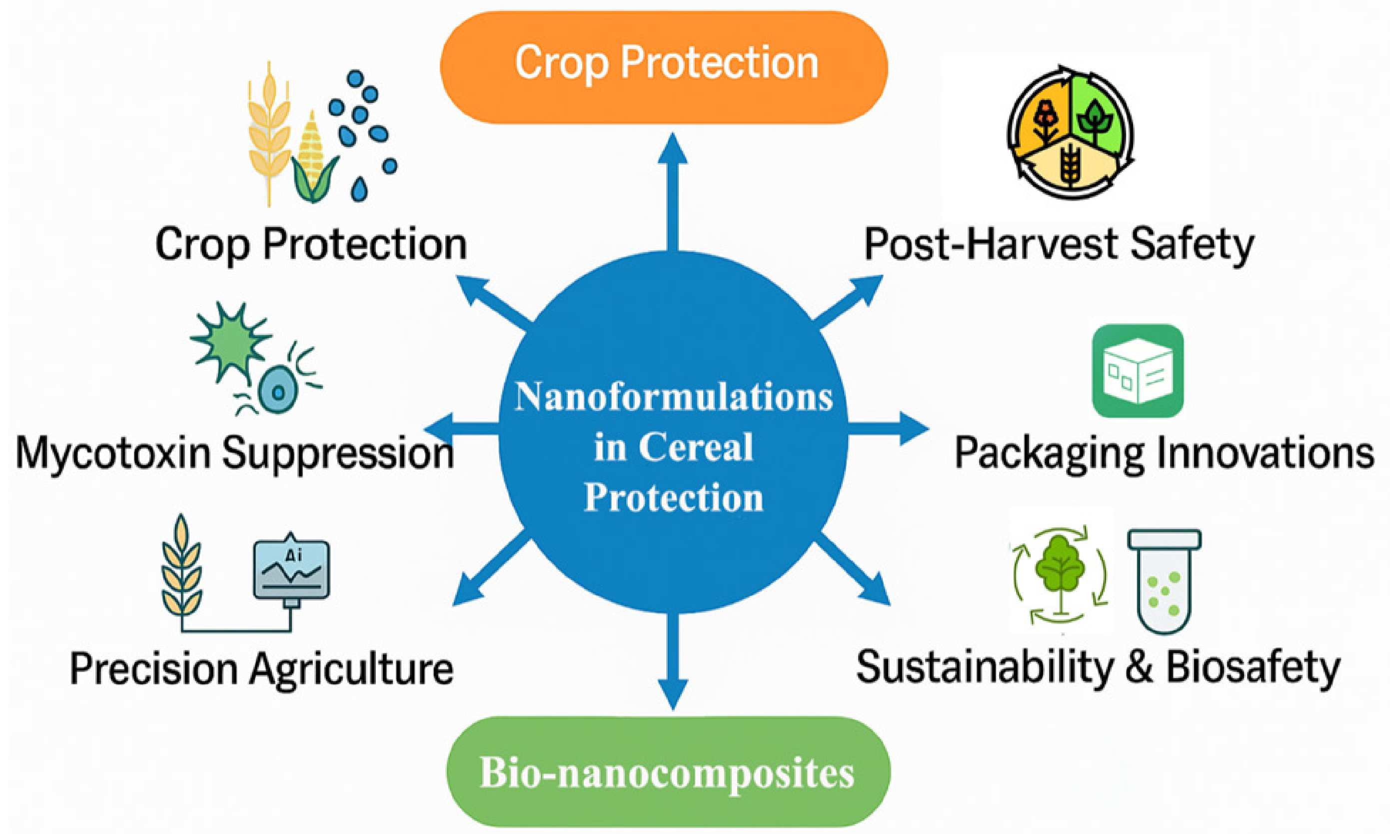

Figure 5: *Applications of bio-nanocomposites for mycotoxins and toxigenic fungi management in cereal systems.*

Safety, toxicity and environmental implications of nanoparticles

Ecotoxicological concerns and nanoparticles persistence

The growing application of carbon nanomaterials in agricultural settings has raised concerns with respect to their probable phytotoxicity. These nanomaterials can penetrate plant tissues, translocate systemically, and destabilize physiological, biochemical, and gene-expression pathways. Therefore, these perturbations can be observed in the form of reduced seed germination, malformed root growth, and alterations in expression of genes related to plant growth (Khan *et al*., 2024). In the case of metal-based NPs, ecotoxicological and environmental persistence are the areas of concern. Despite the researches undertaken on exposure pathways and exposure toxicity mechanisms, there remains a critical gap of comprehensive and long-term risk assessment (Wang *et al*., 2024). Soil, temperature, moisture, and light are in control of plant growth; however, NPs can prevent the early growth by inhibiting germination and seedling formation (Wang *et al*., 2020). The growth of maize root has been suppressed by the ZnO NPs in a particle-selective manner but not by the release of Zn^{2+}, and the inhibitory activity caused by the NPs in cucumber is being mainly ionic (Zhang *et al*., 2015). Toxicity of the metal based NPs has a dose dependence relation whereby ZnO and specifically CuO have been found to be phytotoxic at high levels. The toxicological effects also differ depending on the physicochemical form with AgNPs exhibiting relatively lower chronic toxicity and bioaccumulation, compared to the Ag^{+} ion. These effects are further being species-specifically regulated, and hence there is a dire need to continue with surveillance, although current environmental concentrations of AgNPs are typically below the internationally recognized safety thresholds. Meanwhile, continued surveillance is necessary due to species-specific responses and potential long-term ecological effects (Calisi *et al*., 2022).

Risk assessment and regulatory perspectives

Application of Ag, ZnO, and TiO_2 NPs in the antifungal studies to control mycotoxins production offers opportunities and challenges. The NPs are very reactive and stable hence useful in the fight against toxigenic fungi and mycotoxins that are common in staple foods and are very hazardous to human health (de Oliveira Mallia *et al*., 2022; Singh and Kumar, 2023). Nevertheless, the regulatory procedures and risk evaluations of such applications are complicated, and the multiple issues of biosafety, acceptance of applications by consumers, farmers, and environmental impact need to be addressed to enable NPs extensive application in the food sector (Biswas *et al*., 2022; Mateo *et al*., 2025).

Nanoparticles safety and toxicological concerns involve:

- Evidence indicates that AgNPs can inhibit fungal growth and reduce mycotoxins production. For example, biosynthesized AgNPs mediated by *Juglans regia* have reduced AF levels and improved liver and kidney function markers in an animal study at a dietary dose of 50 µg/kg (Naqvi *et al*., 2023). However, AgNPs may accumulate in plant tissues, and their broader toxicological effects remain insufficiently understood, highlighting the need for further evaluation before large-scale agricultural application (Piecková *et al*., 2021).
- ZnO NPs safety: A commercial mixture of ZnO and metallic NPs hasn't induced any cytotoxicity or inflammatory effect in THP 1 human macrophage cells under the selected concentrations, suggesting that some formulations may be used safely (Mani *et al*., 2022; Fei *et al*., 2025)
- TiO_2 NPs, the available literature does not provide sufficient, directly supported data on their antifungal efficacy or toxicological effects in mycotoxins control. Consequently, definitive conclusions regarding their safety and effectiveness cannot yet be drawn, indicating a clear evidence gap (Noireaux *et al*., 2021).

Regulatory frameworks and guidelines

Management of the use of NPs in agriculture and food is uneven, with some countries having biocide regimes with little specific regulation of nanoforms. The corpus reviews recommend that the rules become harmonized and evaluated on a case-by-case basis.

- Biocide and food safety regulations in place: The European Union is mentioned as a pioneer in integrated food safety and biocide laws that situate risk accountabilities within the food chain, and the provisions within these models are the basis beginnings of dealing with nano-enabled antifungals (Piecková *et al*., 2021).
- Regulatory loopholes and uncertainty: Multiple reviews point to the absence of technical definitions, standardized testing protocols, and clear nano specific regulations on agricultural/food applications, producing regulatory uncertainty on Ag, ZnO, and other nanoformulations (Ogwu and Izah, 2025).
- Nano specific guidance needed the authors suggest the use of life cycle assessment (LCA), ecotoxicology, and standardized toxicological testing in regulatory decision making to analyse nanoforms not based on their bulk forms (Ogwu and Izah, 2025).
- Consumers acceptance and biosafety concerns: Reviews indicate that biosafety data and consumer's acceptance are pre-conditions to regulatory and market acceptances, which means that regulators will demand strong safety dossiers (Ogwu and Izah, 2025).

Risk benefit analysis and future perspectives

In literatures, there are encouraging examples of antifungal/mycotoxins properties of some NP preparations, but there are also considerable gaps in the evidence base that do not allow making conclusive and generalizable risk-benefit assertions. Standardized testing, comparative risk assessment, and targeted regulation should be considered as the priorities of the work in the future.

- Proven benefits: Multiple studies and review findings indicate good antifungal efficacy and mycotoxin synthesis reductions of AgNPs and efficacy markers of ZnO preparations, having the potential to benefit human health and crops when used properly (Piecková *et al*., 2021; Naqvi *et al*., 2023; Fei *et al*., 2025)
- Documented and potential risks: There is evidence of plant tissue deposition of NPs, environmental release issues, and incomplete toxicological data resulting in the ecological and human health hazards not yet able to be preclusively ruled out in most usage cases (Piecková *et al*., 2021; Ogwu and Izah, 2025).

Biodegradable and "green" nanomaterials as safer alternatives

Green chemistry is focused on the development of high-performance processes that reduce or avoid use and formation of hazardous substances throughout the product lifecycle (Kurul *et al*., 2025). In situ generation of NPs using biodegradable, bio-derived reducing and capping materials (e.g. plant polyphenols) can mitigate the risk of handling and provide low-toxicity recyclable nanocatalysts (Shafey, 2020). ZnO and Ag NPs with a variety of morphologies and functionality have been synthesized through plant-mediated synthesis with the use of whole plants or organ/tissue extracts (Manojkumar *et al*., 2023). As an example,

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AgNPs produced using *Hagenia abyssinica* leaf extract has yielded stable crystalline NPs with confirmed structural integrity (Melkamu and Bitew, 2021).

Challenges, limitations and future perspectives

Scale-up and cost-effectiveness

One of the greatest challenges in nanotechnology is scaling up the production of nanostructures (Smitha *et al*., 2009). In terms of the out-scaling, plant/ microorganism-driven-metal NPs (MNPs) production encounters certain obstacles like keeping uniformity (size and shape), reproducibility, purification in an efficient way, and economic feasibility despite being inherently ecofriendly and possibly-affordable option compared to the chemical routes, due to demand of optimized bioreactors and protocols and defeating low yields for a truly industrial scale. In principle cost effectiveness being good (since using natural agents), but the yields are low and the complexities of purification and lack of standardisation raise the costs remarkably to make this approach commercially viable. The barriers to plant-mediated green synthesis of MNPs include the lack of raw plant materials (especially non-cultivated ones), limited large-scale processing equipment, inability to control molecular composition, and heterogeneity of the biochemical profiles of plant extracts (Dikshit *et al*., 2021). Although NPs synthesis is possible through plant tissue cultures -mediated by plant metabolites, several major difficulties lie in the scale-up of the production process because of the variability in the metabolites, and the lack of reproducibility (Anuradha *et al*., 2025). Despite the fact that the regulatory authorities have started to regulate nano-objects such as MNPs, the debate continues to be scarce, and it is mainly directed at the differentiation between traditional-made and green-made NPs (Chávez-Hernández *et al*., 2024). It is important to note that green synthesis methods have appreciable benefits, namely, they are less toxic, ecofriendly, cost-effective, fast, and easy to work with (Dikshit *et al*., 2021).

Role of omics and AI in designing next generation nanoformulations

The next-generation nanobiocomposite formulations (NBFs) are nanotechnology- and biotechnology-based approaches that incorporate better performance, functionality, and sustainability at the nanoscale. They have major strengths such as being ecofriendly, non-toxicity, size on the nanoscale, controllable morphology, and efficient delivery, making them lucrative candidates for safe and sustainable use in agricultural and environmental systems (Sharma *et al*., 2022). The combination of nanotechnology, precision agriculture, and artificial intelligence (AI) makes it possible to conduct real-time monitoring of crops, delivery of the necessary nutrients, and effective resource utilization. Such convergence can be used to develop smart nanoformulations to improve uptake, distribution, and sustainability, which could help to overcome climate-related challenges, enhance the health of soils, and provide a safe and effective agrochemical performance (Ashique *et al*., 2025). NBFs have become a useful tool in the contemporary agricultural settings because of their prospects of application (Vishnu *et al*., 2024).

Artificial intelligence has become one of the revolutionary tools in the agricultural industry, used to forecast crop yields, identify pests, and evaluate crop health in real-time (Goel and Pandey, 2024). AI systems can be used proactively to respond to the emerging mycotoxigenic pathogens against a particular crop when combined with next generation NBFs. Nanosensors, drones, imaging tools, and automated systems with AI constantly scan the field conditions, giving an accurate detection of pests, pathogens, and soil health. There are new applications such as Plantix that enable farmers to take photos of crops, upload them to the AI to evaluate them instantly, identify illnesses and infestations, and not only depend on human assessment (Samal *et al*., 2023). On the other hand, Hasteer *et al*. (2024) study has identified nine key obstacles limiting AI adoption in agriculture, highlighting inadequate skilled labor and harsh climatic conditions as the most substantial factors restricting its effective implementation.

Environmental, human and regulatory considerations

Nanoparticles can threaten plants and soil ecosystems by reducing microbial biomass, enzymatic activity, and diversity, with increasing environmental concentrations raising risks of long-term exposure, persistence, and cumulative ecological impacts (Rajput *et al*., 2018). NPs in fertilizers, pesticides, and food-related products can migrate through the food chain, increasing human exposure, with previous findings like C60 accumulation in rice highlighting potential food-safety risks (Chen *et al*., 2023). Similarly, cerium oxide NPs have accumulated in rice grains, causing nutrient losses, altered grain composition, and reduced antioxidant levels, demonstrating dietary exposure risks and negative impacts on rice nutritional quality (Rico *et al*., 2013). Nanomaterials use in cereals introduces dietary, occupational, and environmental exposure risks. Humans may ingest NPs migrating into edible grain fractions, while absorption varies with particle properties (Naseer *et al*., 2018). Because exposure pathways and toxicokinetics differ widely, each nanoformulation requires thorough, and use-specific toxicological evaluation. Regulating nano-enabled agricultural products is challenging due to limited long-term safety data and lack of standardized testings. European Food Safety Authority (EFSA), Food and Drug Administration (FDA), and Codex require detailed nanomaterial characterization, including particle size, dissolution, migration, and toxicokinetics (Kumari *et al*., 2023; Mukhopadhyay, 2025). EFSA mandates nano-specific risk assessments, while FDA requires safety evidence for nano-enabled food-contact and agricultural materials (Amenta *et al*., 2015). Codex lacks harmonized global nanomaterial guidelines. Inconsistent regulatory criteria and unvalidated exposure models hinder commercialization and underscore the need for clearer global standards.

Conclusions and Recommendations

Nano-formulations are a revolutionary scheme in fighting fungal infections and mycotoxins synthesis in cereal plants, having better efficacy, focused delivery, and minimal environmental hazard compared to the traditional chemical means. Ag, ZnO, and TiO_2 NPs exhibit effective antifungal action by various mechanisms such as membrane disruption, ROS production, and inhibition of enzymes. Nonetheless, there are still serious issues of standardization, long-term safety testing, and harmonization of regulations. Combination of green synthesis techniques, intelligent delivery, and precision agriculture technologies has gigantic potential in sustainable crops protection. Future studies are highly recommended to focus on: (1) full toxicological testing's along the food chain; (2) enforcement of international food safety regulations toward agricultural nanomaterials; (3) lifecycle assessment of nanoformulations production up to environmental fate; (4) optimization of application methods used in field tests; and (5) use of novel strategies of engaging people to deal with consumer's insecurities and promoting the adoption of nanotechnology in global food security projects.

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Novelty Statement

This review is a unique study in which multidisciplinary approaches to nanoformulations use for the control of fungi and mycotoxins production in cereal crops are incorporated, encompassing nanotechnology, phytopathology, food safety, and regulatory science. In contrast to the previous studies, it thoroughly discusses the mechanistic synergies among various types of NPs (Ag, ZnO, and TiO_2) in relation to their specific actions on mycotoxigenic fungi during pre-harvest and post-harvest periods. The review critically analyzes the emerging smart delivery systems, green synthesis methods, and precision agriculture integration, and fills critical knowledge gaps related to risk assessment frameworks and environmental fate. This study represents a comprehensive roadmap to converting nano-enabled laboratory inventions into field-deployable technologies, by integrating current developments with regulatory considerations and commercialization challenges toward the sustainable protection of cereal crops.

Author's Contribution

Mohamed M. Ramadan: Data curation, writing – original draft
Nasr Fawzy Nasr, Mohammed Zakaria Sedik and Mohamed Usama El-Segai: Writing – review & editing
Kamel A. Abd-Elsalam: Supervision

Generative AI and AI-assisted technology statement
The authors attest that no artificial intelligence (AI) or AI-assisted technology was used in the creation of this work. Only figure 4 designed and cited NanoBanana

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