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Mycotoxin Mitigation Using Nanomaterials: A Systematic Review on Removal Efficiency, Material Characteristics, and Key Influencing Factors

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Abstract

Background and Objective: Mycotoxins are toxic secondary metabolites produced by fungi. Despite many efforts to control fungal growth, they frequently contaminate agricultural products, food, and feed, posing a critical health risk for humans and animals. Physical, chemical, and biological methods to mitigate mycotoxin levels across matrices are limited, so recent studies have focused on innovative, efficient, and cost-effective materials to remove or adsorb mycotoxins. Given their unique properties, nanomaterials have been introduced as a promising tool for adsorbing mycotoxins and reducing their toxic effects; this systematic review evaluated data from studies on the efficiency of different nanomaterials in removing mycotoxins.

Materials and Methods: Relevant studies were systematically searched in PubMed, Web of Science, and Scopus up to 12 August 2025, and only English-language articles were included. Two investigators independently screened titles, abstracts, and full texts according to eligibility criteria defined by the PICOS framework. Data on nanomaterial type, matrix, mycotoxin type, nanomaterial concentration, and mycotoxin reduction percentage were extracted, and reduction rates were summarized descriptively as unweighted means, overall and for each nanomaterial subgroup; no meta-analysis or formal risk-of-bias assessment was performed.

Results and Conclusion: Based on the results, the most used nanomaterials were metal-based nanomaterials > nanocomposites > organic nanomaterials > carbon-based nanomaterials. Most studies targeted aflatoxins, followed by ochratoxin A, fumonisin (FB_1, FB_2, FB total), zearalenone, and deoxynivalenol. The included studies reported varying levels of mycotoxin reduction across different media and food/feed matrices, although these effects did not necessarily reflect direct adsorption and could also result from inhibited fungal growth or toxin production. Nanomaterials therefore show promising in vitro mycotoxin-reducing efficiency; their safety and suitability for food and feed applications remain to be established.

What is "already known" on this topic:	• Mycotoxins regularly contaminate agricultural products, food, and feed, posing a critical health risk for humans and animals. • Physical, chemical, and biological methods for mitigating mycotoxin levels are limited. • Nanomaterials have been introduced as a promising tool for adsorbing mycotoxins.
What this article adds:	• Metal-based nanomaterials were the most used; most studies targeted aflatoxins. • Nanomaterials show promising in vitro mycotoxin-reducing efficiency; their safety for food and feed remains to be established.

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1. INTRODUCTION

Mycotoxins are toxic substances generated by some fungal strains, mainly from the *Aspergillus*, *Penicillium*, and *Fusarium* Sps, as secondary metabolites. These microbial toxins are associated with acute and chronic diseases and a high death rate in both humans and animals [1, 2]. To date, more than 400 types of mycotoxins have been recorded, among which aflatoxins, ochratoxin, zeara-lenone, deoxynivalenol, and fumonisins are the most commonly found in food items. Major mycotoxin contam-ination is observed in cereals (corn, wheat, rice), nuts, and oilseeds [3]. Additionally, some main animal products can contain considerable levels of mycotoxins due to contam-inated feed [4, 5]. Updated global prevalence data also indicate a high co-occurrence of mycotoxins in food; for example, maize can be contaminated with both aflatoxins and fumonisins, posing synergistic health risks. According to the joint report of the Food and Agriculture Organization and the World Health Organization, mycotoxins have been quantified in approximately a quarter of cereal crops and 60-80% of grains worldwide, resulting in the annual waste of one billion tons of food and feed [6, 7]. Mycotoxins can occur from farm to fork, requiring control, management, and preventive actions throughout the food processing chain. The most influential factors for contamination include climatic conditions (temperature, moisture), agricultural practices from pre- to post-harvest, and storage [8]. To protect human and animal health and reduce exposure to this critical contamination, countries have established mandatory regulations to limit mycotoxin concentrations in food and feed [9]. To mitigate mycotoxin contam-ination in food and feed commodities, preventive str-ategies aim to inhibit toxin-producing fungal growth and employ methods and materials to reduce mycotoxin levels in contaminated items. These strategies rely on physical, chemical, and biological methods [10]. Recently, resistant crop varieties, along with good agricultural practices and good manufacturing practices, have been considered to control mycotoxin contamination. Controlling relative humidity and temperature during storage can limit fungal growth and mycotoxin production from harvest to post-harvest stages, as can con-trolling insect invasion in pre- and post-harvest stages (Figure 1). However, neglecting critical points in agricultural practices and the food production chain may increase mycotoxin incidence [11-13]. To date, mycotoxin contamination, especially aflatoxins, has been annually reported as one of the top ten hazards in food and feed by the Rapid Alert System for Food and Feed. This means that despite efforts to control fungal growth and prevent mycotoxin production, it remains a critical problem in food and feed items and poses a global hazard to human and animal health. In this regard, implementing strategies to reduce mycotoxins in contaminated food and feeds is crucial [14-16]. Myco-toxin adsorbents are sub-stances that can remove toxin molecules by preventing their absorption in the gastro-intestinal tract, thus reducing their harmful effects. These adsorbent agents include inorganic or organic materials that bind mycotoxins to their surface or degrade /transform them into lower-toxicity metabolites [17-20]. Nanotechnology offers new opportunities to detect, prevent, and remove mycotoxin contamination [21,22]. This is due to the unique properties of nanomaterials, such as a high surface area-to-volume ratio, tunable physico-chemical properties, and functional versatility [18-20,23,24]. Over the past decade, advances in nanotech-nology have introduced highly efficient adsorbents [25-29]. Emerging nanomaterials based on carbon, poly-saccharides, polymers, or metal particles offer vast active surfaces for adsorbing targeted mycotoxins [30]. Because the size, shape, and polarity of a mycotoxin molecule influence its interaction with different binders, nano-materials show promise for myco-toxin adsorption because of their large surface area and ability to interact with both polar and non-polar com-pounds [31-33]. The growing interest in nanomaterials as mycotoxin adsor-bents stems from their high specific surface area and tunable surface chemistry, which facilitate interactions with a wide range of mycotoxins. Furthermore, surface functionalization can enhance adsorption selectivity toward specific mycotoxins [34, 35].

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Figure 1. Major practices to prevent mycotoxin contamination during pre-harvest, harvest, post-harvest, and the marketing chain. Integrating these practices across the entire value chain is essential to minimize mycotoxin contamination and ensure food and feed safety.

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1.1. Nanomaterial Types for the Adsorption of Mycotoxins

1.1.1. Carbon-based nanostructures

Carbon nanomaterials are generally stable, inert, and can adsorb both polar and non-polar mycotoxins. They also remain stable colloid across a range of pH conditions [20, 36]. The most used nanomaterials in this class for mycotoxin elimination were graphene and its derivatives (native graphene, reduced graphene, and graphene oxide), carbon nanotubes, fullerenes, fibers, and nanodiamonds.

1.1.2. Metal nanoparticles

The strong adsorption capacity of metal-based nanoparticles is related to their desirable pores, vast specific surface area, and conjugation affinity. In this regard, growing applications have established them as mycotoxin adsorbents [37, 38]. Metal and metal oxide nanoparticles have been used as antifungal agents and mycotoxin adsorbents in the mycotoxin control framework. The most studied metal and metal oxide nanoparticles in this field are Ag NPs, Se NPs, Fe NPs, Cu NPs, ZnO, SiO_2, TiO_2, CuO, MgO,- and NiO.

1.1.3. Chitosan-based nanomaterials

Chitosan is a natural, nontoxic, biodegradable polysaccharide that has attracted attention as a promising material for mycotoxin elimination. Chitosan, used alone or with other nanomaterials, has shown a specific capacity for mycotoxin removal [36, 39]. Chitosan is also widely used in edible coatings to preserve food quality [40].

1.1.4. Nanocomposites

Nanocomposites are hybrid materials composed of nanoscale inorganic fillers integrated within or coated by organic polymers, offering enhanced surface area, tunable surface chemistry, and improved mechanical/thermal stability, leading to superior adsorption performance for diverse mycotoxins. Mycotoxin adsorption onto nanocomposites can proceed via hydrogen bonding, Van der Waals forces, electrostatic interactions, π–π interactions, chelation or complexation, and pore confinement [41, 42].

1.1.5. Magnetic nanoparticles

Magnetic nanoparticles, especially when incurporated into nanocomposites, can offer high adsorption capacity and facilitate easy separation due to their magnetic properties [43, 44]. Magnetic chitosan-based composites have also been applied as sorbents for contaminants in dairy beverages [45]. This systematic review focused on major nanomaterials proposed as binders and their efficiency in reducing mycotoxin concentrations across different matrices (Figure 2).

2. MATERIALS AND METHODS

2.1. Data Sources and Search Strategy

We systematically searched PubMed, Web of Science, and Scopus up to 12 August 2025 and included only English-language articles. Two investigators (AA and SZ) independently screened the titles, abstracts, and full-text articles to identify eligible studies. The keywords considered for the systematic search were: (mycotoxin OR aflatoxin OR ochratoxin A OR patulin OR fumonisins OR zearalenone OR trichothecenes) AND (nanomaterial OR nanostructure OR nanoparticle OR nano) AND (reduction OR binding OR mitigation OR removal). The full database-specific search strategies are provided in Table 1. This systematic review did not involve people, humans, or animals as participants; therefore, we did not need to register the review protocol with PROSPERO.

2.2. Study Selection

We defined inclusion and exclusion criteria using the PICOS framework (population, intervention/exposure, comparator, outcome, and study design). Published studies were considered eligible for inclusion in the present systematic review according to the following criteria: (1) evaluated the effects of nanomaterials, nanoparticles, and nanocomposites and did not use other nanostructures, such as nano-emulsions, on mycotoxin reduction; (2) reported the extent of mycotoxin reduction, whether resulting from toxin adsorption or degradation, or from the inhibition of fungal growth and the consequent prevention of mycotoxin production, rather than reporting adsorption capacity alone; (3) investigated the effects of nanomaterials on mycotoxin reduction in food, or culture media; (4) did not investigate nanomaterials for mycotoxin detection; (5) did not investigate the effects of nanomaterials on mycotoxin reduction in vivo or via feeding to animals and biological or cell-based gastrointestinal models. We excluded articles that did not meet the criteria (Table 2).

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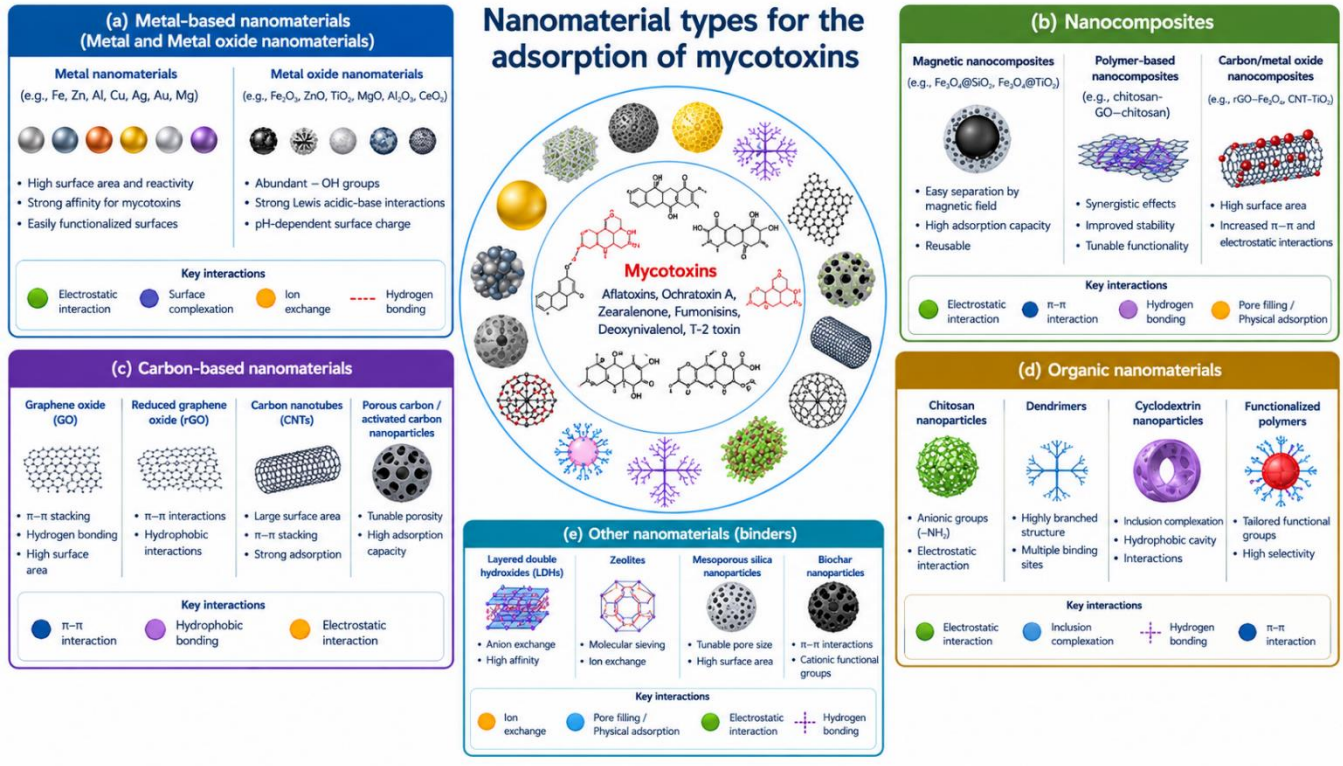


Figure 2. Nanomaterial types for the adsorption of mycotoxins. Their performance depends on nanomaterial type, environmental conditions, and matrix, offering promising strategies for mycotoxin decontamination.

Table 1. List of the reasons for excluding studies.

1	**Other methods of aflatoxin reduction (n=29)**
2	Not relevant intervention (n=9) [46, 47]
3	Not sufficient information (n=5)
4	News, Book chapter, and Patent (n=2)
5	Review (n=4)
6	On molds (n=3) [48]
7	In rats (n=1) [49]

Table 2. Database-specific search strategies.

1	PubMed: (mycotoxin OR aflatoxin OR "ochratoxin A" OR patulin OR fumonisins OR zearalenone OR trichothecenes) AND (nanomaterial OR nanostructure OR nanoparticle OR nano) AND (reduction OR binding OR mitigation OR removal); fields: Title/Abstract; filter: English; searched up to 12 August 2025.
2	Web of Science: TS= ((mycotoxin OR aflatoxin OR "ochratoxin A" OR patulin OR fumonisins OR zearalenone OR trichothecenes) AND (nanomaterial OR nanostructure OR nanoparticle OR nano) AND (reduction OR binding OR mitigation OR removal)); filter: English; searched up to 12 August 2025.
3	Scopus: TITLE-ABS-KEY ((mycotoxin OR aflatoxin OR "ochratoxin A" OR patulin OR fumonisins OR zearalenone OR trichothecenes) AND (nanomaterial OR nanostructure OR nanoparticle OR nano) AND (reduction OR binding OR mitigation OR removal)); filter: English; searched up to 12 August 2025.

2.3. Data Extraction

Two authors extracted data from the included articles. The authors discussed any conflicts to reach agreement. The authors extracted data from each study based on the following characteristics: first author's name, publication year, type of nanomaterial, type of food/medium, type of mycotoxin, nanomaterial concentration used, and mycotoxin reduction percentage. When a study tested several nanomaterials, mycotoxins, matrices, or doses, each combination was extracted as a separate study arm. Reduction

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percentages were recorded as reported (concentration units were not converted); adsorption capacity (mg/g) was not extracted. Regarding nanomaterial type, the main subgroups included metal-based (metal and metal oxide) nanomaterials, nanocomposites, carbon-based nanomaterials, organic nanomaterials, and other nanomaterials.

2.4. Data Analysis

Mycotoxin reduction efficiency was expressed as the percentage decrease in toxin concentration reported by each study and distinguished from adsorption capacity (mg/g). Each study arm was treated as one observation, with the midpoint used for reported ranges. Simple unweighted arithmetic means were calculated overall and by mycotoxin and nanomaterial subgroup, without adjustment for sample size, dose, replicates, or matrix. Given the heterogeneity of the included studies, the synthesis was descriptive rather than a meta-analysis, and mean values were interpreted cautiously rather than as a basis for ranking nanomaterials.

3. RESULTS AND DISCUSSION

3.1. Systematic Search

The literature search yielded 55 records eligible for inclusion in this systematic review [2,17,19,31,32,39, 41-44, 50-94]. We excluded five full-text articles because of insufficient information, and Table 2 lists the reasons for exclusion at all stages.

3.2. Characteristics of Original Articles

Table 3 presents the characteristics of the 55 articles included in this systematic review, comprising 121 study arms. The investigated nanomaterials included metal-based nanomaterials (n = 21), nanocomposites (n = 17), organic nanomaterials (n = 9), carbon-based nanomaterials (n = 5), and other nanomaterials (n = 3). The mycotoxin reductions reported in these studies may have resulted from adsorption or binding, degradation, or inhib-ition of fungal growth and the consequent prevention of mycotoxin production, or a combination of these mechanisms. Figure 3 shows the distribution of studies investigating metal-based nanomaterials for mycotoxin reduction.

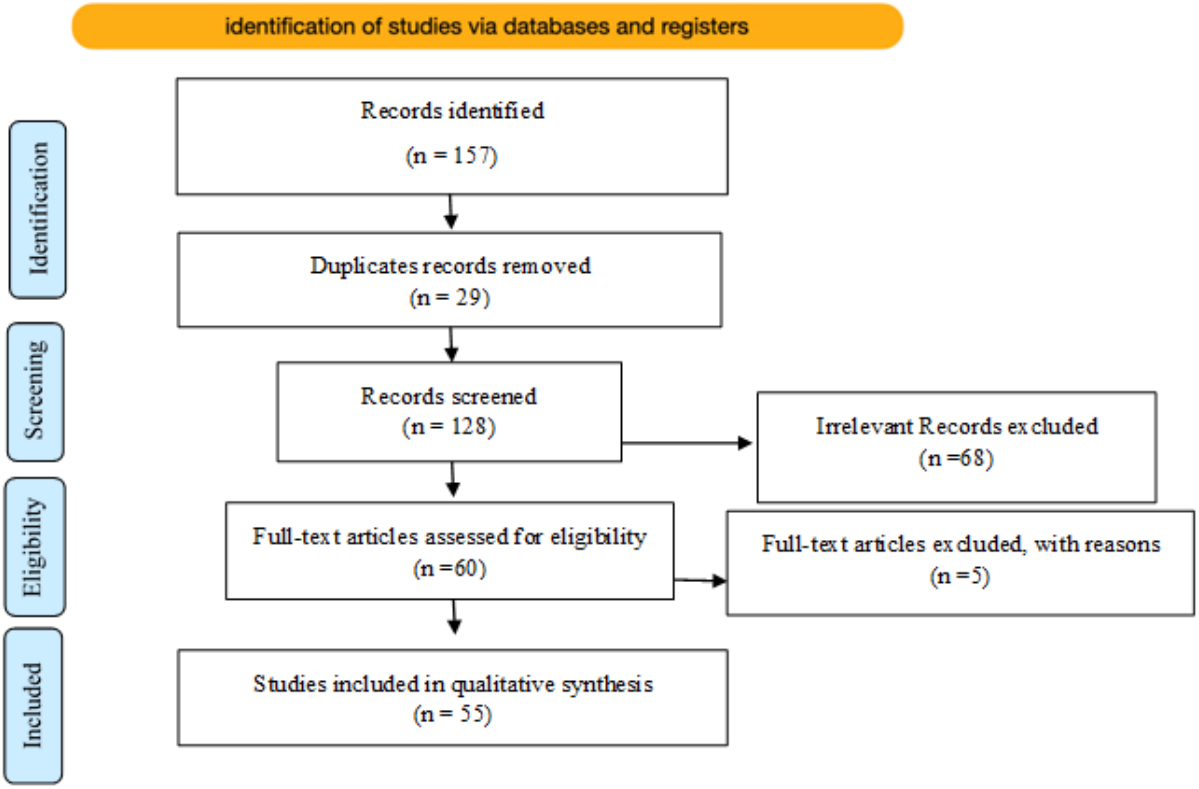


Figure 3. Literature search and study selection process for inclusion in the systematic review.

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Regarding the mycotoxin type, most studies (39 studies) were conducted on aflatoxins (AFB_1, AFB_2, AFG_1, AFG_2, AF total, AFM_1) reduction using nanomaterials; 9 studies on Ochratoxin A (OTA), 8 studies on fumonisin (FB_1, FB_2, FB total), 6 studies on zearalenone (ZEA), 5 studies on deoxynivalenol (DON), and 5 studies on other types of mycotoxins, including Fusaric acid, Nivalenol, Fumagillin, Gliotoxin, Neosolaniol, T_2 toxin, fusarin C, moniliformin, Alternaria toxins, patulin, and trichothecenes.

Regarding the matrix used to investigate the binding capacity of mycotoxins, 21 studies were performed on food and feed products (milk, palm kernel cake, apple juice, pistachio nuts, oils, barley, cucumber, corn seeds, maize grain, water, animal feed, Romy cheese, wheat grain, rice grain, grape juice), and 34 studies were conducted on media (aqueous simulator and phosphate buffer) and culture media (Table 3).

Table 3. The characteristics of included articles in systematic review

Ref	Year	Nanomaterial	Concentration/dose (as reported)	Mycotoxin	Matrix	Reduction %
[50]	2020	AgNPs	25–100 ppm	AFB_1 AFB_2 AFG_1 AFG_2	Culture medium	92–100
[51]	2021	Nano sea salts Nano table salt	2.50%	AFB_1	Rice grain	84.86 95.8
[52]	2023	AgNPs	1.5–3%	AFB_1	Wheat grain	92.92–95.35
[42]	2019	PVP -TA NPs GMLP/PVP -TA NPs	–	AFB_1	Simulated gastric-intestinal fluid	75–99.5
[53]	2016	AgNPs	220 µg	OTA	Medium	52.18–58.87
[54]	2020	Fe-NPs Cu-NPs Ag-NPs	100 µg/mL	AFB_1	Medium	43.9–100
[55]	2025	Walnut shells NPs Almond shell NPs	10 mg/mL	AFB_1	Medium	83.81–93.7
[56]	2025	SiO_2 NPs	100 and 200 mg/kg	Fusaric acid	Culture medium	100
[57]	2020	AgNPs	100 ppm	Nivalenol Fumagillin Gliotoxin Neosolaniol	Medium	60.69–99.86
[58]	2016	AgNPs	3 mg	AFG_1 AFG_2 AFB_1 AFB_2 OTA	Medium	58.76–79.8
[19]	2025	ZnO/yeast cell wall core-shell	–	AFB_1	Medium	55.4
[59]	2021	Natamycin-loaded alginate nanoparticles	–	AFT	Romy cheese	78.6
[60]	2024	SeNPs	–	AFB_1 AFB_2 AFG_1 AFG_2 T2 toxin Fumonisin B_1 ZEA Fusarin C Moniliformin DON	Animal feed	84.79–100
[61]	2019	Nanocomposites Fe_3O_4	–	ZEA FB_1 AFB_1	Medium	54–98

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Ref	Year	Nanomaterial	Concentration/dose (as reported)	Mycotoxin	Matrix	Reduction %
[62]	2024	Magnetic Nanocomposites Fe_3O_4	–	DON OTA ZEA FB_1 AFB_1	Water	55–95
[63]	2019	Nanoparticles	–	AFB_1	Medium	80
[2]	2019	SeNPs	–	OTA	Culture medium	40–50
[64]	2018	ZnO NPs	100 µg/g	AFB_1	Culture medium Maize grain	69–99.7
[65]	2020	Graphene oxide	10 µg/mL	AFB_1 ZEA DON	Medium	65–90
[66]	2019	SeNPs	–	TeA AOH Fumonisin B_1 DON	Medium	63–83
[67]	2020	Agaricus extracts nano Pleurotus sp. extract	–	AFB_1	Culture medium Corn seeds	46.32–72.04
[68]	2024	Nano-urea	3%	AFB_1	Corn kernels Maize grains	78.3–83.36
[69]	2025	Lignin-Chitosan-Iron Nanocomposite	1 mg/mL	AFB_1	Medium	95
[41]	2015	Nanocellulose by poly-lysine	–	Fumonisin B_1	Wheat Rice Maize Cucumber	80–95
[43]	2020	Magnetic graphene composite	–	AFB_1	Contaminated oils	88.82
[70]	2020	Magnetic nano-zeolite	–	AFB_1 Zearalenone OTA Deoxynivalenol	Barley	1.8–>99
[93]	2023	Encapsulated Zataria multiflora's essential oil	6.7 mg/mL	AFB_1	Pistachio nut Medium	92–99
[71]	2025	Nanocomposite hydrogel	–	AFB_1	Medium	94
[72]	2025	Nanocomposite pumpkin seed oil and its chitosan-Arabic gum nanoparticles	–	AFT	Beef sausage	66.6
[73]	2019	AgNPs	5.6 µg/mL	AFB_1 OTA	Culture medium	100
[94]	2019	Diatomite with sulfur-functionalized graphene oxide (GO-SH) nanosheets	–	Patulin	Apple juice	>90
[39]	2019	Chitosan nanoparticles with EHP phenolic compounds	–	AFB_1	Culture medium	68.6
				AFB_2		69.7
		Chitosan nanoparticles with EMMP phenolic compounds		AFB_1		87.3
				AFB_2 AFG_1		82.6–100
[74]	2020	Silica nanoparticles	–	AFM_1	Medium	65–89
[75]	2024	Chitosan nanoparticles	0.5–3.5 mg	AFB_1	Milk Medium	91
[17]	2023	Nano-MgO	–	OTA	Grape juice	91
[76]	2022	Nano-MgO	–	OTA	Wine	92
[32]	2023	TiO_2-NPs	–	AFB_1	Medium	49.34
[77]	2021	Se-chitosan/L-cysteine nanoparticles	1–9 mg	Patulin	Juice simulator Apple juice	98–100
[78]	2022	ZnO-NPs	0.8–2 g/kg	Total fumonisins	Maize grains	71–99
[79]	2020	CuNPs AgNPs	≥ 100 mg/L ≥ 20 mg/L	Fumonisin B_1 Fumonisin B_2	Culture medium	100

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Ref	Year	Nanomaterial	Concentration/dose (as reported)	Mycotoxin	Matrix	Reduction %
[31]	2018	Magnetic Graphene Oxide modified with Chitosan	0.03 g	AFB_1 OTA ZEA DON	Medium	70–90
[44]	2017	Magnetic graphene oxide nanocomposite	–	ZEA HT_2 T_2	Palm kernel cake	37.17–69.57
[80]	2025	Fe_3O_4/Chitosan/Curcumin/Postbiotics	–	AFM_1	Milk	72.8
[81]	2024	Fe_3O_4/Cs/MoS_2/Lac NPs	–	AFM_1	Milk	96.8
[82]	2022	Thiourea-polygalacturonic acid nanocomplex	–	Patulin	Apple juice	91.35
[83]	2023	Mesoporous silica nanoparticles	2.0 mg/mL	AFB_1 AFT	Medium	70
[84]	2023	Magnetic nanobentonite		AFB_1 AFB_2 AFG_1 AFG_2	Medium	94.32–98.46
[85]	2020	Carbon-encapsulated nano-zero valent iron (CE-nZVI)	–	Patulin	Medium Apple juice	99.75 89
[86]	2020	Cell walls immobilized on nano-silica entrapped in alginate	–	AFM_1	Medium	53–87
[87]	2024	Nanobody magnetic Fe_3O_4 nanoparticles	–	AFG_2	Medium	96.9–97.1
[88]	2025	Carbon-doped iron-based nanozyme	–	AFB_1	Medium	90
[89]	2019	Zinc oxide Honey -zinc oxide	–	AFB_1	Maize grains	96.42 94.64
[90]	2019	AgNPs	–	AFB_1	Culture medium	56.45
[91]	2015	Nanocellulose	–	Fumonisin B_1	Culture medium	55
[92]	2024	Fullerenol nanoparticles	–	AFB_1	Culture medium	60

Reduction (%) indicates the decrease in mycotoxin concentration, not adsorption capacity. Concentration/dose is reported as originally presented; '–' indicates not reported.

3.3. Mycotoxin Reduction Rate

The mean mycotoxin reduction (%) considering the reduction of mycotoxins by nanomaterials was: aflatoxins (84.34%; 39 studies), ochratoxin A (79.72%; 9 studies), fumonisin (87.16%; 8 studies), zearalenone (75.71%; 6 studies), and deoxynivalenol (53.47%; 5 studies) (Figure 4). Researchers mostly detected and quantified mycotoxins using HPLC, ELISA, and ELISA/HPLC.

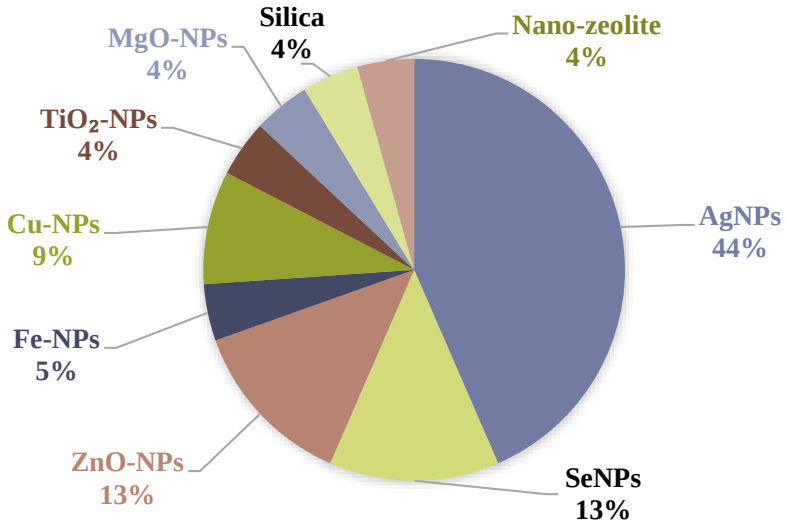


Figure 4. Studies reporting the use of metal-based nanomaterials to reduce mycotoxins.

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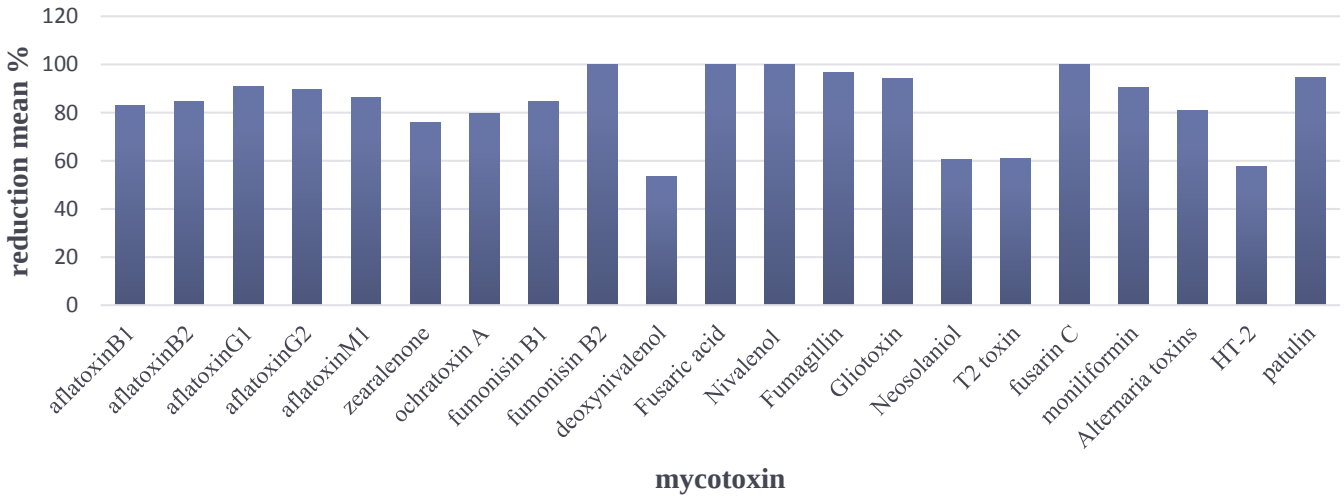


Figure 5. Reduction of mycotoxin concentration in studied matrices using all nanomaterial types in reviewed studies.

The overall mean mycotoxin reduction using all studied nanomaterials was 81.67%. The mean mycotoxin reduction (%) for each nanomaterial class was as follows: metal-based nanomaterials (81.07%; 21 studies), nanocomposites (83.55%; 17 studies), carbon-based nanomaterials (76.55%; 5 studies), and organic nanomaterials (72.61%; 9 studies) (Figure 5). These unweighted means are descriptive only: the classes differ in the number of studies, doses, matrices, mycotoxins, and mechanisms of reduction, and we did not statistically test differences between them

3.4. Discussion

Mycotoxins are a critical multidisciplinary issue in chemistry, food, plant, and animal sciences. However, fewer studies address nanotechnology from these disciplines. Nanoscale materials could be considered an alternative because of their unique properties and the opportunities they offer. Recently developed nanomaterials are now used commercially in medicine and other industries. Several researchers have experimentally studied the use of nanotechnology to eliminate microbial toxins, but their results have not yet been systematically reviewed. Given the high prevalence of mycotoxins in food and feed, efficient methods to remove contamination help improve product safety. This systematic review of experimental studies is to our knowledge, the first study to gather relevant data assessing the efficiency of nanomaterials in reducing fungal toxins from edible and non-edible matrices. Our findings showed that, in the included studies, nanomaterials reduced mycotoxin concentrations by up to 100%. Based on their chemical nature, the nanomaterials used included carbon-based nanomaterials, nanocomposites, metal-based nanomaterials, and organic nanomaterials. The included studies reported decreases in concentrations of different mycotoxins across various matrices. These reduction percentages are not equivalent to adsorption capacity (mg/g) and, depending on the study, may reflect adsorption, degradation, or inhibition of fungal growth or toxin production.

Beyond summarizing removal efficiency, this review adds three elements that, to our knowledge, earlier work on nano-adsorbents has not combined. First, it applies a systematic, PICOS-based search and a uniform extraction scheme to experimental data, so reduction rates for the five major mycotoxins and the four nanomaterial classes can be examined alongside each study's matrix, dose, and analytical method. Second, by explicitly separating the reported percentage reduction from adsorption capacity, it shows that part of the available evidence cannot be interpreted as binding alone, because a decrease in toxin concentration may also reflect degradation or inhibition of fungal growth and toxin production; this limits direct ranking of materials and shifts the central question from which nanomaterial removes the most toxin to under which conditions and through which mechanism it does so. Third, it quantifies reporting gaps rather than only success rates: 34 of the 55 included studies did not report the dose, and none provided toxicological data. These

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evidence gaps, rather than the high mean reduction rates, define the priorities for the next generation of studies.

3.4.1. Mycotoxin adsorption mechanisms

The mycotoxin adsorption by nanomaterials process is explained by several proposed mechanisms, mostly inferred from the physicochemical characteristics of the materials and from adsorption behavior rather than directly confirmed. The main proposed mechanisms include: 1) Physical Adsorption, which operates through non-covalent, weak intermolecular forces such as van der Waals interactions and pore-filling. Mesoporous silica nanoparticles containing pore channels (2-50 nm) can physically trap mycotoxin molecules of compatible size. 2) Chemical Adsorption, which involves the formation of strong, specific chemical bonds between the mycotoxin and functional groups on the nanomaterial's surface. Electrostatic Interactions: These occur between charged toxin molecules and oppositely charged nanomaterial surfaces. For example, at certain pH levels, the carboxyl groups of ochratoxin A (OTA) are negatively charged and are strongly attracted to the positively charged surfaces of chitosan nanoparticles. Hydrogen Bonding and Complexation/Chelation: These are other patterns of this mechanism. 3) π-π Stacking Interactions, which are specific and highly effective interactions where the π-electron systems of aromatic rings on the adsorbent and adsorbate overlap (Figure 6). Carbon-based nanomaterials, such as activated carbon nanotubes and graphene oxide, can physically adsorb mycotoxins because of their large surface areas, graphitic structures, and π-electron clouds. Furthermore, surface engineering through amino-functionalization or molecularly imprinted polymers can enhance adsorption capacity and selectivity [20, 37, 62, 95]. In studies of antifungal nanomaterials, a decrease in toxin concentration may also result from degradation or from inhibition of fungal growth and toxin biosynthesis rather than from adsorption.

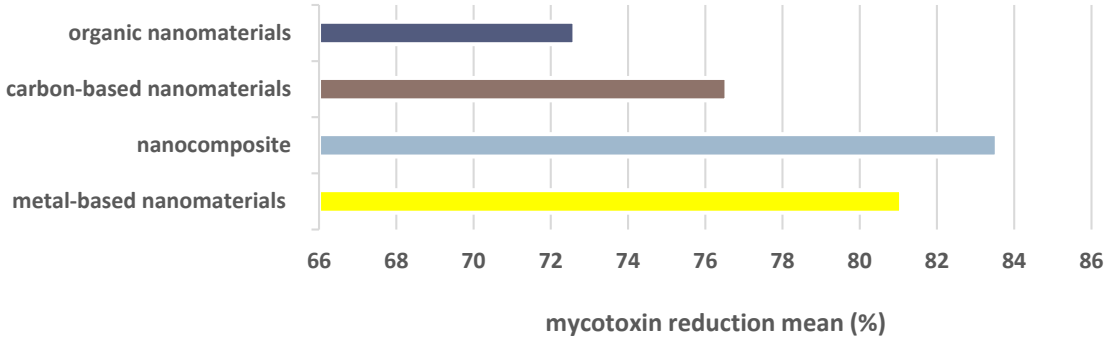


Figure 6. Unweighted mean mycotoxin reduction rate by nanomaterial class in the included studies.

3.4.2. The influencing factors on mycotoxin adsorption

Adsorption, the ability of a nanomaterial to bind mycotoxins, is crucial to its effectiveness. Some nanomaterials can be engineered to bind to specific mycotoxins, which is important for targeted detoxification. Besides, nanomaterials used in food or feed applications should be stable and biocompatible. The nanomaterials and developed nanostructures reduced mycotoxins, depending on major variables such as concentration, pH, contact time, matrix/media type, and mycotoxin concentration (Figure 7).

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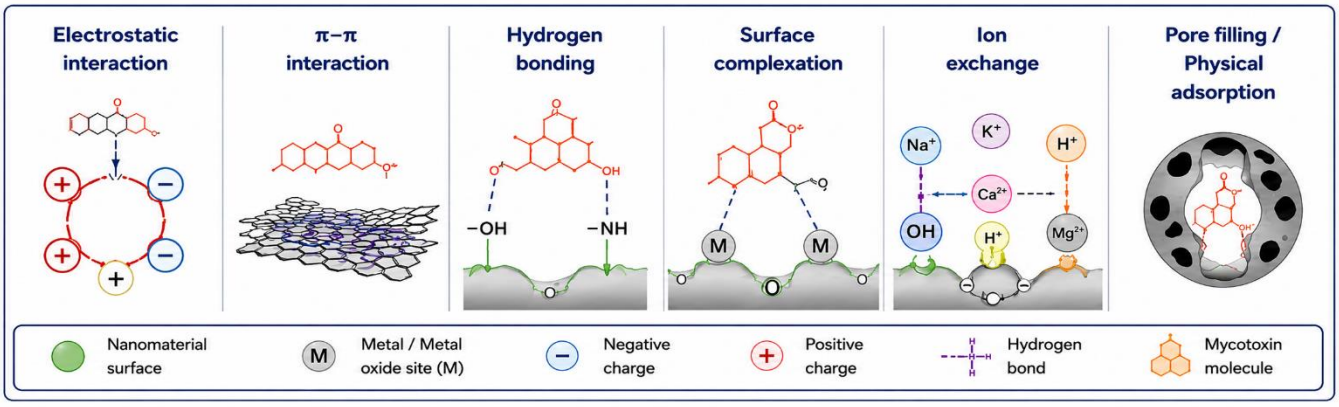


Figure 7. The mechanisms of mycotoxin adsorption by nanomaterials.

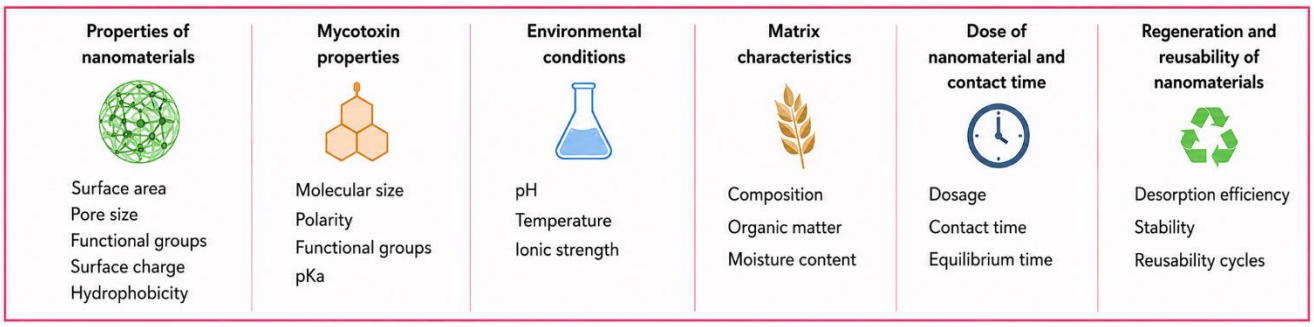


Figure 8. Factors influencing the mycotoxin adsorption efficiency by nanomaterials.

3.4.3. Effect of initial concentration of mycotoxins

Most studies found that the initial toxin concentration strongly influenced reduction rates. Adsorption experiments with varied initial AFB_1 concentrations showed that removal of AFB_1 using magnetic graphene composite decreased from 93.88% to 88.12% when the AFB_1 content increased from 5 µg/L to 25 µg/L [43]. Because nanomaterials have a defined surface area, they can adsorb only a limited amount of mycotoxin molecules; therefore, removal efficiency may decrease at higher initial toxin concentrations.

3.4.4. Effect of nanomaterial types

As the results show, the highest mean mycotoxin reduction rate (83.55%) was related to the nanocomposite type of nanomaterials (Figure 8); however, the differences among classes were small, were not tested statistically, and are confounded by differences in dose, matrix, mycotoxin, and study design, so they do not indicate an intrinsic superiority of any class. Nanocomposites may offer a high surface area-to-volume ratio and a large interfacial area for mycotoxin binding, and, as multiphase structures containing components such as polymers, ceramics, and metals, they may perform better as adsorbent materials. Included studies mostly used chitosan nanostructures in nanocomposite mixtures with different adsorbent materials, which showed high efficiency in adsorbing mycotoxins. Furthermore, activated carbon, bentonite, hydrogels, gums, and polylysine mixed with other nano-adsorbent materials were investigated to reduce mycotoxin levels in matrices. In several cases, it was concluded that a mixture of materials synergistically increases mycotoxin reduction. However, all analyses should consider the effects of specific nanostructures in nanocomposites and the matrix effects of experimental variables. In addition, metal-based nanomaterials showed a notable mycotoxin-reducing effect across different food and media samples. The remarkable properties of metal-based nanomaterials, such as an extremely high specific surface area and abundant, highly active surface sites related to their nanoscale size and tunable surface chemistry, make them desirable for binding various agents. Carbon-based nanomaterials and

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organic nanomaterials also demonstrated binding efficiency in the studied research. Because nanomaterial mycotoxin-reducing performance is multi-faceted, it may be enhanced by a synergistic combination of maximized surface area, tunable surface chemistry, and unique quantum-scale properties.

3.4.5. Effect of nanomaterial dosage

Mycotoxin adsorption efficiency also depends on nanomaterial dosage. Studies reported that increasing nanoparticle (Ag-NPs, Fe-NPs, and Cu-NPs) content increased AFB_1 adsorption. In addition, using nanoparticles individually provided higher AFB_1 removal than using them together [54]. In a similar study, AFB_1 adsorption (up to 94%) was significantly enhanced by higher nano-composite content (10 to 20 mg/mL) [43]. Obviously, higher adsorbent concentrations increase the number and availability of active sites, resulting in greater mycotoxin adsorption from matrices.

3.4.6. Effect of temperature

Temperature is another effective factor in removal efficiency, depending on the matrix or medium containing mycotoxins. In most reviewed studies, raising the temperature to a critical point increased mycotoxin removal by nanomaterials. Higher temperatures improved AFB_1 removal from contaminated oil samples (81.60% to 95.64%) using a graphene composite as the temperature increased from 25°C to 60°C. However, temperatures above 60°C showed a decreasing trend in AFB_1 adsorption [43]. It was reported that the AFB_1 adsorption capacity of metal nanoparticles increased with rising temperature. The obtained feature indicated the endothermic nature of the adsorption process. At higher temperatures, increased toxin-molecule motility likely provides more opportunities for adsorption at nanostructure active sites [54].

3.4.7. Effect of pH

pH influences mycotoxin adsorption by altering nanomaterial surface charge and mycotoxin ionization, thereby affecting electrostatic interactions. For example, OTA adsorption onto positively charged nano-MgO is pH-dependent [17, 76]. Because these effects vary by adsorbent–mycotoxin pair, no general pH trend can be established, and each system must be optimized.

3.4.8. Effect of contact time

Most studies showed that mycotoxin adsorption with nanomaterials is time-dependent. However, the reviewed plots showed that adsorption was fast during the initial contact times and continued over time to a definite equilibrium point, at which maximum adsorption occurred. During the subsequent contact period, no significant additional adsorption occurred. This suggests that the active sites in the mycotoxin binder become occupied during the initial contact time. Sampling at different times showed that AFB_1 binding to the titanium dioxide nanoparticle-based nanostructure is time-dependent, with maximum adsorption achieved after 48 hours of contact time [32, 96-99].

3.4.9. Other related factors in mycotoxin adsorption

Matrix type and composition, including solid or liquid state, may have influenced the reported mycotoxin reduction rates. Results from in vitro studies using naturally or artificially contaminated matrices may also differ from those in real-world systems. The included studies varied in nanomaterial characteristics, dose, mycotoxin type, matrix, experimental conditions, and analytical methods. These factors were not adjusted for; therefore, class means should not be used to rank nanomaterials. Dose was unreported in 34 of 55 studies. Observed reductions may have involved adsorption, chemical degradation, fungal growth inhibition, and reduced toxin production (e.g., antifungal coatings [100]). Their relative contributions could not be established. No formal risk-of-bias assessment was performed because no widely accepted tool specific to in vitro mycotoxin-binding studies was identified. Thus, reported reduction rates should be interpreted descriptively, not as definitive evidence of efficacy. Future studies should improve methodological reporting and use standardized assessment approaches where appropriate.

3.4.10. Practical applications of nanomaterial-based adsorbents for mycotoxin mitigation

Nanomaterial-based adsorption technologies offer opportunities for post-harvest management. Incorporating nanomaterials into storage platforms, packaging materials, and active preservation methods could reduce fungal growth and mycotoxin production during storage

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and transportation. Because nanocomposites with both antifungal and binding properties can provide dual protection against contamination, they can improve product quality and extend shelf life. Furthermore, nanomaterials can be integrated into monitoring and remediation efforts in food safety management. Multifunctional nanomaterials that can simultaneously detect and adsorb mycotoxins may facilitate rapid contamination mitigation. Such approaches could promote risk management programs and support regulatory compliance throughout the food and feed production chain. Overall, the reviewed in vitro and food-matrix studies suggest that nanomaterials may help reduce mycotoxin contamination in food and feed. However, demonstrated efficacy and applicability in food matrices do not establish gastrointestinal stability, toxicological safety, or regulatory acceptability, which still require evaluation.

Another development that single-endpoint reduction rates do not capture is the shift toward recoverable, multifunctional nanomaterials. Magnetic nanostructured agents can be separated from liquid matrices with an external magnetic field. Still, when tested in beer, milk, and distiller's dried grains with soluble, the matrix slightly decreased adsorption capacity for some toxins [62]; capacities determined in simple aqueous solutions should therefore not be transferred directly to foods. In parallel, adsorption–degradation hybrid systems immobilize photocatalytic or enzymatic modules on selective adsorbents such as metal–organic frameworks, covalent organic frameworks, and molecularly imprinted polymers, enriching trace toxins at the surface and converting them in situ, which may reduce the required dose of detoxifying agent [101]. This concept is already reflected in some of the included studies, such as nanobody-functionalized magnetic nanoparticles for selective aflatoxin capture [87] and a carbon-doped iron-based nanozyme that both adsorbs and degrades AFB_1 [88]. However, degradation adds a requirement that adsorption does not: the structure and toxicity of the transformation products must be verified, because a decrease in the parent toxin does not by itself demonstrate detoxification. Future comparative studies should therefore report adsorption capacity (mg/g) with isotherm and kinetic analysis, regeneration over repeated cycles, and the toxicity of reaction products, in addition to percentage reduction.

3.4.11. Safety and environmental considerations

Safety is essential for food and feed applications, yet the included studies provided no toxicological data. Metal and metal oxide nanoparticles (e.g., Ag, ZnO, Cu, CuO, and TiO_2) can migrate into food, particularly when added directly and not subsequently removed. Potential toxicity, migration, and environmental release or accumulation therefore require case-specific assessment before application, in accordance with risk-assessment guidance for nanomaterials in the food and feed chain [102].

4. CONCLUSION

Overall, the included in vitro studies demonstrated that nanomaterials can reduce mycotoxin concentrations by up to 100%, with potential for multi-mycotoxin removal and enhanced selectivity through surface modification. However, substantial study heterogeneity, the absence of formal quality assessment and direct comparisons with conventional adsorbents, and the exclusion of in vivo and biological gastrointestinal studies limit conclusions regarding their comparative performance, safety, and practical applicability. Future research should prioritize standardized efficacy assessments, toxicological and environmental safety, gastrointestinal fate, and scalable, cost-effective production, supported by clear regulatory frameworks to facilitate their responsible application in food and feed systems.

5. DECLARATION STATEMENTS

5.1. Acknowledgments

None.

5.2. Conflicts of Interest

The authors declare no conflict of interest.

5.3. Author Contributions

Setayesh Zamanpour and Anna Abdolshahi wrote the article and reviewed it.

5.4. Funding

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5.5. Data Availability Statement

Dara are available by any request from corresponding author.

5.6. Ethics

Not applicable.

5.7. Use of Artificial Intelligence Chat-bots

Artificial Intelligence (AI) chatbots were used solely to improve the language, grammar, spelling, and clarity of the manuscript and to assist in the design of some figures. The authors reviewed, edited, and verified all AI-assisted text and figure elements and take full responsibility for the accuracy, originality, integrity, and final content of the manuscript.

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کاهش مایکوتوکسین با استفاده از نانومواد: مرور نظام‌مند بر کارایی حذف، ویژگی‌های مواد و عوامل مؤثر کلیدی

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چکیده

سابقه و هدف: مایکوتوکسین‌ها ترکیبات سمی هستند که توسط قارچ‌ها به‌عنوان متابولیت‌های ثانویه تولید می‌شوند. با وجود تلاش‌های فراوان برای کنترل رشد قارچ‌ها، این سموم به‌طور منظم محصولات کشاورزی، مواد غذایی و خوراک دام را آلوده می‌کنند و خطری جدی برای سلامت انسان و دام به شمار می‌روند. روش‌های فیزیکی، شیمیایی و زیستی موجود برای کاهش سطح مایکوتوکسین‌ها در ماتریکس‌های مختلف محدودیت دارند؛ از این رو مطالعات اخیر بر مواد نوآورانه، کارآمد و مقرون‌به‌صرفه برای حذف یا جذب مایکوتوکسین‌ها متمرکز شده‌اند. با توجه به ویژگی‌های منحصربه‌فرد نانومواد، این ترکیبات به‌عنوان ابزاری امیدبخش برای جذب مایکوتوکسین‌ها و کاهش اثرات سمی آن‌ها معرفی شده‌اند؛ این مرور نظام‌مند داده‌های مطالعات مربوط به کارایی نانومواد مختلف در حذف مایکوتوکسین‌ها را ارزیابی کرد.

مواد و روش‌ها: مطالعات مرتبط به‌صورت نظام‌مند در پایگاه‌های PubMed، Web of Science و Scopus تا ۱۲ آگوست ۲۰۲۵ جست‌وجو شدند و تنها مقالات انگلیسی‌زبان وارد مطالعه شدند. دو پژوهشگر به‌طور مستقل عنوان‌ها، چکیده‌ها و متن کامل مقالات را مطابق معیارهای ورود تعریف‌شده بر پایه چارچوب PICOS غربالگری کردند. داده‌های مربوط به نوع نانوماده، ماتریکس، نوع مایکوتوکسین، غلظت نانوماده و درصد کاهش مایکوتوکسین استخراج شد و نرخ‌های کاهش به‌صورت توصیفی و در قالب میانگین‌های بدون وزن‌دهی، به‌طور کلی و برای هر زیرگروه نانوماده، خلاصه شدند؛ متاآنالیز یا ارزیابی رسمی خطر سوگیری انجام نشد.

یافته‌ها و نتیجه‌گیری: بر اساس نتایج، بیشترین نانومواد مورد استفاده به‌ترتیب شامل نانومواد پایه فلزی > نانوکامپوزیت‌ها > نانومواد آلی > نانومواد پایه کربنی بودند. بیشتر مطالعات بر آفلاتوکسین‌ها تمرکز داشتند و پس از آن اکراتوکسین A، فومونیسین (FB_1، FB_2 و FB کل)، زیرالنون و دئوکسی‌نیوالنول قرار داشتند. مطالعات واردشده در محیط‌ها و ماتریکس‌های مختلف غذایی/خوراکی سطوح متفاوتی از کاهش مایکوتوکسین را گزارش کردند، هرچند این اثرات لزوماً بیانگر جذب مستقیم نبودند و می‌توانستند ناشی از مهار رشد قارچ یا تولید سم نیز باشند. بنابراین نانومواد کارایی امیدبخشی در کاهش مایکوتوکسین در شرایط آزمایشگاهی نشان می‌دهند؛ ایمنی و مناسب‌بودن آن‌ها برای کاربردهای غذایی و خوراکی هنوز باید اثبات شود.

واژگان کلیدی: جذب، آلودگی، مایکوتوکسین، نانوماده، کاهش آلودگی

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