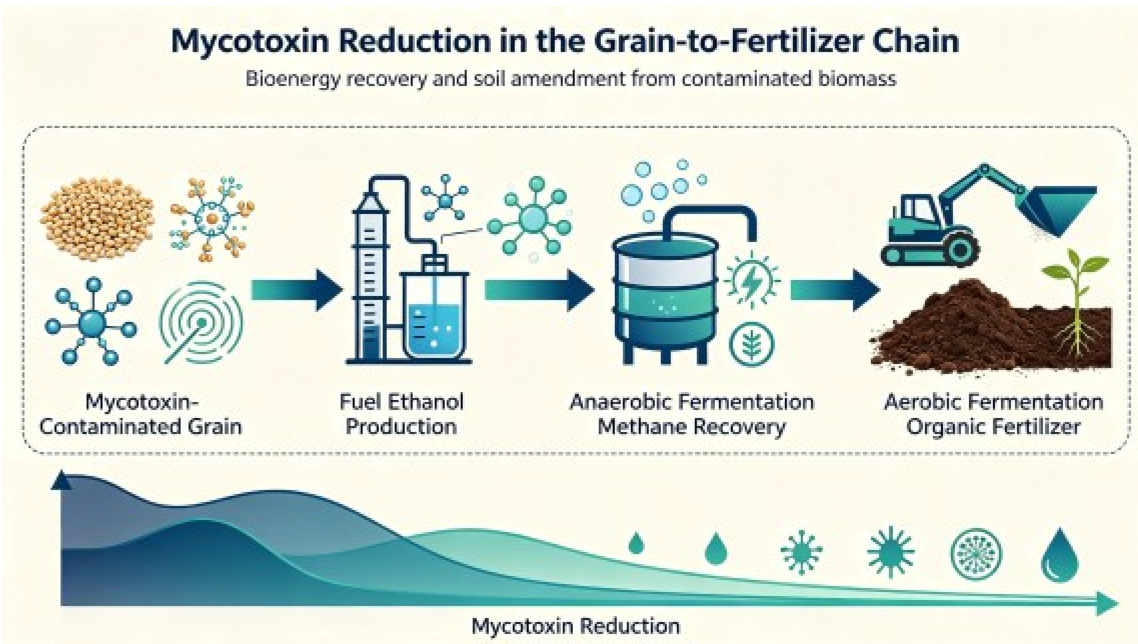
Degradation of Mycotoxins During the Production of Fuel Ethanol, Biogas, and Organic Fertilizer from Whole Grains

Xinwei Wang,[a,b] Shuangqi Tian,[a,b,*] Xuan Qin,[b] Jing Lu,[c] and Zhanpeng Liu,[a,b]

DOI: 10.15376/biores.21.4.Wang

* *Corresponding author: tianshuangqi2002@126.com*

GRAPHICAL ABSTRACT



Degradation of Mycotoxins During the Production of Fuel Ethanol, Biogas, and Organic Fertilizer from Whole Grains

Xinwei Wang,[a,b] Shuangqi Tian,[a,b,*] Xuan Qin,[b] Jing Lu,[c] and Zhanpeng Liu,[a,b]

During the production of fuel ethanol, biogas, and organic fertilizer from whole grains, mycotoxins in the feedstock raise complex issues regarding product safely. In fuel ethanol production, processes such as grinding, liquefaction, and fermentation can cause structural transformations or reductions in the levels of certain toxins (such as zearalenone and vomitoxin); however, degradation products may remain in the distillers' grains protein feed, affecting the safety of the byproduct. During the biogas fermentation stage, anaerobic microbial communities can further degrade some toxins through enzymatic reactions and metabolic processes. The degradation efficiency is significantly influenced by feedstock characteristics, process parameters, and toxin types, and small amounts of toxins or their transformation products may still remain in the digested liquid. In the subsequent organic fertilizer production process, the high-temperature phase of composting helps reduce residual toxins, and the synergistic action of aerobic microorganisms enhances degradation. However, certain mycotoxins may not be completely degraded or may generate unknown metabolites, posing potential ecological and health risks after application to farmland. Elucidating the degradation mechanisms, transformation pathways, and product safety of mycotoxins during multi-stage sequential treatment is important for ensuring pollution control across the entire industrial chain and the safe utilization of resource-recycled products.

DOI: 10.15376/biores.21.4.Wang

Keywords: Mycotoxins; Degradation; Fuel Ethanol; Organic Fertilizer; Whole Grains

Contact information: a: Food Laboratory of Zhongyuan, Luohe, 462300, China; b: College of Food Science and Technology, Henan University of Technology, Zhengzhou, 450001, China; c: Department of Molecular Sciences, Swedish University of Agricultural Sciences, PO Box 7015, SE-75007 Uppsala, Sweden;
** Corresponding author: tianshuangqi2002@126.com*

INTRODUCTION

During their growth, harvest, and storage in the field, whole grains are susceptible to infection by fungi such as *Fusarium* and *Aspergillus*, which produce mycotoxins that pose a serious threat to human and animal health (Pande *et al.* 2025). These secondary metabolites are widely distributed and have become a major challenge in the field of global food safety (Gurikar *et al.* 2023). A wide variety of mycotoxins have been detected in whole grains and their products, with contamination by deoxynivalenol (DON), zearalenone (ZEN), aflatoxin (AFT), and fumonisin (FUM) being particularly prominent (Sadhasivam *et al.* 2017; Shi *et al.* 2024). Contamination varies by grain type. For example, rice is primarily contaminated with ochratoxin A and deoxynivalenol, while corn is mainly contaminated with fumonisin and deoxynivalenol, and wheat has a high detection rate of deoxynivalenol and its derivatives (Akimsha *et al.* 2026). It is noteworthy that the phenomenon of mixed contamination of multiple toxins is widespread. Over 80% of the grain samples are simultaneously contaminated with two or more mycotoxins (Tournas and Niazi 2018; Gurikar *et al.* 2023). This "co-contamination" effect may result in synergistic or additive toxicity, increasing the complexity of risk assessment and control measures (Shi *et al*. Yu 2019). Toxic producing fungi are ubiquitous in soil and crop residues and can erupt on a large scale in suitable weather conditions such as high temperature and humidity. Even with commercially available fungicides, it is difficult to reliably prevent fungal infections before harvest. When grains are harvested and enter the storage stage, the situation is completely different. At this stage, chemical fungicides are rarely directly sprayed onto grain piles for food security reasons (Yao *et al.* 2026).

To address mycotoxin contamination across the entire grain industry chain, multi-tiered prevention and control strategies have been developed around the world, covering the entire process from farm to dining table. These strategies encompass traditional measures such as the breeding of disease-resistant varieties, field disease management, rapid post-harvest drying, and precise control of storage conditions (Bereda 2025). In recent years, biological control and microbial degradation technologies have garnered significant attention due to their environmentally friendly and highly efficient nature (Wang *et al.* 2023). Fermentation using specific beneficial microorganisms can significantly reduce toxin levels in grains. For example, during the fermentation process, specific strains such as *Lactobacillus plantarum* can achieve a degradation percentage of up to 98% for fumonisin B1 (FB1) and 84% for T-2 toxin (Anukul *et al.* 2014). Furthermore, solid-state fermentation of wheat bran using *Bacillus subtilis* not only effectively inhibits the growth of toxin-producing fungi (such as *Fusarium graminearum*), preventing the production of new toxins during processing, but it also enhances the nutritional quality and antioxidant capacity of wheat bran (Wang *et al.* 2025). Meanwhile, although deoxynivalenol levels in grains are relatively higher under conventional farming practices, there is no significant difference in overall toxin contamination levels between organic and conventional farming systems. This implies that prevention and control efforts must encompass all production models (Bernhoft *et al.* 2022).

Converting stale grain or whole grains exceeding pollution limits into fuel ethanol is a key approach to ensuring food security and achieving efficient resource utilization (Xu *et al.* 2025). This process not only effectively utilizes grain stocks that have exceeded their storage period, preventing them from re-entering the food market, but it also provides a stable supply of raw materials for the bioenergy industry (Albahri *et al.* 2023). Currently, the process routes for producing fuel ethanol from whole grains (such as over-stored rice) are primarily divided into two categories: direct fermentation of whole rice grains with husks, and mixed fermentation with other feedstocks such as corn and cassava (Hoang and Nghiem 2021). In actual production, specific technical challenges posed by whole grain feedstocks must be addressed. For example, rice husks are hard in texture, which not only increases the difficulty of crushing and causes equipment wear, but it also reduces the starch concentration in the fermentation system, resulting in low ethanol content in the mature mash (Favaro *et al.* 2017). Furthermore, the high protein content in grains – particularly the high levels of gluten in rice, which has strong foaming properties – easily causes tray blockages during distillation, forcing frequent shutdowns for cleaning and severely impacting production continuity and economic efficiency (Hao *et al.* 2025). To address these issues, the industry has continuously explored and optimized pretreatment processes (such as dehulling and protein separation) and fermentation technologies (such as concentrated mash fermentation and simultaneous saccharification and fermentation), striving to ensure stable plant operation while improving ethanol yield (Zhang *et al.* 2026).

The large amounts of distiller's grains, spent grain, and byproducts from whole-grain processing (such as rice husks and wheat bran) generated during fuel ethanol production serve as ideal feedstocks for producing biogas and organic fertilizer (Chavan *et al.* 2024). Through anaerobic digestion technology, these organic-rich byproducts can be converted into clean energy-biogas (primarily composed of methane), while the post-fermentation digestate and effluent serve as high-quality organic fertilizers, achieving cascading utilization of materials and energy (Ferdous *et al.* 2020). The method of feedstock pretreatment directly affects biogas yield, for example, preparing silage corn using a finer shredding method can reduce fiber content and improve its digestibility and biogas yield (Gao *et al.* 2020). In the process of using whole grains to prepare ethanol, biogas, and compost, only the AFB1 content of dry distillers' grains (DDGS) in the ethanol production process is required to be less than 50 μ g/kg, and there is no specific requirement for the toxin content in biogas and compost (Green *et al.* 2015). This model, which closely integrates whole-grain utilization, energy production, and ecological agriculture, provides a sustainable pathway to addressing food security, the energy crisis, and agricultural non-point source pollution (Ćurčić *et al.* 2025).

The detoxification of mycotoxins in the preparation of ethanol, biogas, and compost from grains is a complex process that mainly relies on enzymatic degradation by microorganisms. At the same time, environmental factors such as temperature and pH value can significantly affect the efficiency of this process. Physical adsorption also plays a certain role, but it is not the main mechanism (Murtaza *et al.* 2024). *Bacillus amyloliquefaciens* screened from composted soil can produce extracellular enzymes that can degrade 80.6% of aflatoxin B1 within 48 h (Wei *et al.* 2015). The temperature, pH, and metal ions can affect the activity of the enzyme. In a biogas fermentation system for treating contaminated silage feed, the new carboxylesterase genes that are directly related to the effective degradation (about 60%) of fumonisin. At the same time, the degradation rate of aflatoxin B1 by the system also reached about 54% (Ferrara *et al.* 2021). The cell wall components (such as peptidoglycan) of some microorganisms (such as lactic acid bacteria) can adsorb mycotoxins through hydrophobic interactions or covalent bonds, forming toxin bacterial complexes and reducing their harm. This is a supplementary detoxification method during the fermentation process, characterized by minimal impact on grain nutrition (Murtaza *et al.* 2024).

DEGRADATION OF MYCOTOMIN DURING THE PREPARATION OF FUEL ETHANOL FROM WHOLE GRAINS

As whole grains serve as a key raw material for fuel ethanol production, concerns regarding their safe utilization are growing (Green *et al*. 2015). During the process of producing fuel ethanol from whole grains, the migration and degradation of mycotoxins directly impact the safety of the final product, particularly the feed safety of DDGs, a byproduct of ethanol production, and their soluble components (Berwian *et al*. 2025). In recent years, extensive research on the degradation mechanisms of mycotoxins during fuel ethanol fermentation has revealed that multiple pathways, including irradiation, ultrasound, biodegradation, enzymatic conversion, and physical adsorption to reduce toxin levels (Fig. 1) (Ouyang *et al*. 2024; Yao *et al*. 2026). As shown in Table 1, however, the stability of different mycotoxins during fermentation varies significantly.

Table 1. Degradation of Mycotoxins during the Preparation of Ethanol from Whole Grains

Types of Mycotoxins	Grain Sources	Degradation/Conversion Status	Main Technologies/ enzymes/strains	Reference
DON	Barley	Conversion rate 52.4% -58.1%: DON was transformed into a less toxic form (3ADON) by transgenic yeast expressing *TRI101* or *TRI201* genes	Transgenic yeast expressing *TRI101/TRI201*	Khatibi *et al.* (2011)
DON	Wheat	The highest degradation rate is 51.5%: the combined application of amylase and xylanase during the saccharification process achieved the degradation of DON	Starch enzyme+Xylanase	Juodeikiene *et al.* (2009)
FUM	Corn	Almost completely eliminated (about 100%): significantly reduced in the traditional cooking (high-pressure heat treatment) process	Traditional technology (high-pressure cooking)	Kłosowski *et al.* (2023)
ZEN	Corn	Degradation rate of about 95% -100%: also attributed to the high-pressure heat treatment process in traditional technology	Traditional technology (high-pressure cooking)	Kłosowski *et al.* (2023)
DON	Corn	Degradation rate of 77% -97%: achieved in the high-pressure heat treatment process of traditional technology	Traditional technology (high-pressure cooking)	Kłosowski *et al.* (2023)
AFT	Cron	During the fermentation process, there is little degradation: toxins do not enter the distilled ethanol, but concentrate in the distiller's grains. Chemical reagents (NaOH, NH_4OH, etc.) are required for subsequent detoxification	Traditional distillation technology	Lillehoj *et al.* (1979)
Total Aflatoxin	DDGS	Degradation rate of 52.8%: achieved through secondary fermentation of corn ethanol by-products by *Trichoderma reesei*	*Trichoderma reesei*	Sun *et al.* (2021)
DON	DDGS	Degradation rate of 92.9%: achieved through secondary fermentation of corn ethanol by-products by *Trichoderma reesei*	*Trichoderma reesei*	Sun *et al.* (2021)
ZEN	DDGS	Degradation rate of 89.2%: achieved through secondary fermentation of corn ethanol by-products by *Mucor indicus*	*Mucor indicus*	Sun *et al.* (2021)

Note: DON represents deoxynivalenol, FUM represents fumonisin, ZEN represents zearalenone, AFT represents aflatoxin, DDGS represents dry distillers' grains.

Some mycotoxins, such as DON, exhibit strong resistance to fermentation, while others, such as ZEN, are relatively converted by microorganisms (You *et al*. 2024). A thorough understanding of the degradation patterns of mycotoxins during whole-grain fuel ethanol production holds significant theoretical and practical value for guiding the safe utilization of contaminated raw materials and ensuring the feed safety of byproducts (Murtaza *et al*. 2025).

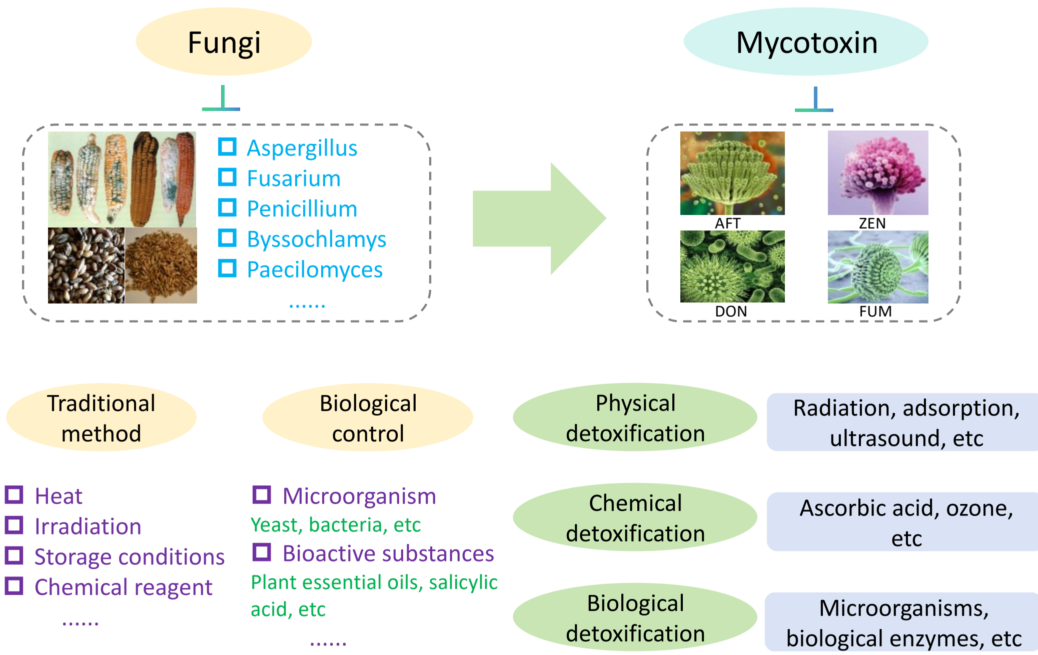


Fig. 1. Origins of mycotoxins' accumulation, its control and detoxification methods

The Main Mechanisms of Mycotoxin Degradation

The degradation of mycotoxins during ethanol fermentation is a complex biochemical process involving the synergistic interaction of multiple mechanisms (Gavahian *et al.* 2021). The microbial degradation is the primary pathway for toxin reduction, and its mechanisms can be categorized into two types: adsorption and enzymatic conversion (Liu *et al.* 2024). In the adsorption-binding mechanism, components of the microbial cell wall-such as polysaccharides, peptidoglycans, and glucans-form non-covalent bonds with toxin molecules, thereby immobilizing the toxins on the surface or within the bacterial cells and rendering them biologically inactive (Okoye *et al*. 2026). Lactic acid bacteria exhibited particularly significant adsorption of ZEN. Cell wall fragments from strains such as *Lactobacillus brevis* could adsorb 50% to 70% of ZEN (Murtaza *et al*. 2024). In contrast, *Bacillus* species adsorbed only 10% to 20% of the toxin, but exhibited higher degradation efficiency, suggesting that different microbial species employ distinct detoxification strategies (Li *et al.* 2023).

Enzymatic conversion is another key pathway for mycotoxin degradation, wherein extracellular or intracellular enzymes secreted by microorganisms convert toxin molecules into less toxic or non-toxic products (Loi *et al*. 2017). During enzyme-assisted ethanol fermentation, the combined use of xylanase and amylase not only improved fermentation efficiency, but it also significantly promoted DON degradation. When a novel combination of amylase and xylanase was used to saccharify contaminated wheat, the detoxification percentage of DON during fermentation reached as high as 51.5% (Juodeikiene *et al.* 2009). During *Lactobacillus* fermentation, various enzymes, such as amylase, xylanase, and protease, were involved in the degradation of DON and its derivatives. Notably, differences in the enzymatic composition and activity among different strains directly determined the efficiency of toxin degradation and the characteristics of the resulting products (Trakselyte-Rupsiene *et al.* 2022).

Degradation Characteristics of Different Mycotoxins

Various mycotoxins exhibit significantly different degradation patterns during ethanol fermentation, which is closely related to their molecular structure, chemical stability, and the metabolic capacity of microorganisms (Ji *et al.* 2016). DON, a representative of the B-type trichothecenes, exhibited strong stability during ethanol fermentation. When ethanol fermentation was carried out using *Saccharomyces cerevisiae*, only 53% of DON and T-2 toxin were removed, with 41% entering the fermentation broth and 6% remaining in the solid residue (Chlebicz and Śliżewska 2020). In corn ethanol production, the degradation efficiency of DON was significantly influenced by process conditions. When using a spray-cooking heater, the reduction in DON was approximately 20%, whereas the degradation effect was poorer when using a plate heat exchanger. This indicated that the intensity and method of heat treatment had a significant impact on DON degradation (Paneru *et al*. 2025). Nevertheless, by selecting an appropriate combination of enzyme preparations, the detoxification rate of DON could be increased to over 50% (Zhu *et al*. 2017; Hou *et al*. 2023). Zearalenone is relatively easily biotransformed during ethanol fermentation. ZEN could be converted into α-zearalenol and β-zearalenol during *Saccharomyces cerevisiae* fermentation, with conversion rates reaching 69% and 8.1%, respectively. This conversion primarily occurred on the first and second days of fermentation, indicating that yeast possesses strong ZEN metabolic capacity (Keller *et al.* 2015). *Bacillus* species were significantly more efficient at degrading ZEN than lactic acid bacteria. The *Bacillus* species could achieve nearly complete degradation of ZEN after 6 h of cultivation at pH 6 and 37 °C. This finding provided a new technical approach for the biological detoxification of ZEN-contaminated grains (Zhang *et al*. 2016).

The degradation patterns of fumonisin during ethanol fermentation differ from those of other toxins. During corn ethanol production, fumonisin could be almost completely eliminated through high-temperature, high-pressure treatment using conventional technologies. This might be related to the relatively low thermal stability of fumonisin (Sosa *et al*. 2013). Additionally, conventional dehulling could significantly reduce fumonisin levels in corn, bringing them below the safety limited set by the European Union. These results suggested that the synergistic interaction between raw material pretreatment and the fermentation process was crucial for the effective removal of fumonisin (Bowers and Munkvold 2014).

Key Process Factors Affecting the Efficiency of Mycotoxin Degradation

The efficiency of mycotoxin degradation during ethanol fermentation is influenced by multiple process factors, among which raw material characteristics, strain selection, enzyme formulation, and process conditions are key determinants of detoxification efficacy (Giacomini *et al*. 2023). The initial contamination level of the raw materials and the form of the toxins affect the difficulty of degradation. When the DON concentration in wheat reached as high as 3,950 µg/kg, a significant proportion of the toxin remained in the distillers' grains (Santos *et al.* 2021). Furthermore, the presence of bound toxins added to the complexity of detoxification, different *Lactobacillus* strains exhibited significant differences in their ability to degrade DON conjugates (Nabgan *et al.* 2025).

The selection of fermentation strains is a core factor influencing toxin degradation efficiency. Different microorganisms exhibit varying degradation capabilities for various toxins (Mishra *et al.* 2021). Brewing yeast has relatively limited degradation activity toward DON but demonstrates good conversion capacity for ZEN (Wall-Martínez *et al.* 2019). *Lacticaseibacillus casei*, a member of the *Lactobacillus* genus, exhibited excellent degradation performance for DON and its derivatives, while *Bacillus* species, particularly *Bacillus megaterium*, demonstrated extremely high degradation efficiency for ZEN (Adácsi *et al.* 2022). This suggests that in practical applications, appropriate fermentation strains can be selected based on the contamination characteristics of the raw materials, or even multi-strain composite fermentation can be adopted to enhance detoxification effects (Marzano *et al.* 2022).

The combined use of enzyme preparations plays a significant role in improving the degradation efficiency of mycotoxins. Adding xylanase to traditional amylase not only increases ethanol yield but also significantly promotes DON degradation. This may be because xylanase can degrade the hemicellulose components in grain cell walls, releasing bound toxins and thereby improving toxin accessibility and biotransformation efficiency (Vidal *et al.* 2017). Furthermore, thermal processing significantly influenced toxin degradation, and high-temperature treatment using a spray-cooker was more effective at reducing toxin levels than using a plate heat exchanger. However, it was worth noting that while certain process conditions could effectively reduce toxin levels in the raw material, toxins might re-accumulate in the by-products (Li *et al.* 2026).

DEGRADATION OF MYCOTOXINS DURING THE PREPARATION OF BIOGAS FROM WHOLE GRAIN FERMENTATION WASTIE RESIDUE

As a key feedstock for bioenergy conversion, the safety assessment of whole-grain fermentation residues has attracted increasing attention. During the deep processing of grains, mycotoxins may accumulate in the residues due to contamination of the raw materials (Peles *et al.* 2019).

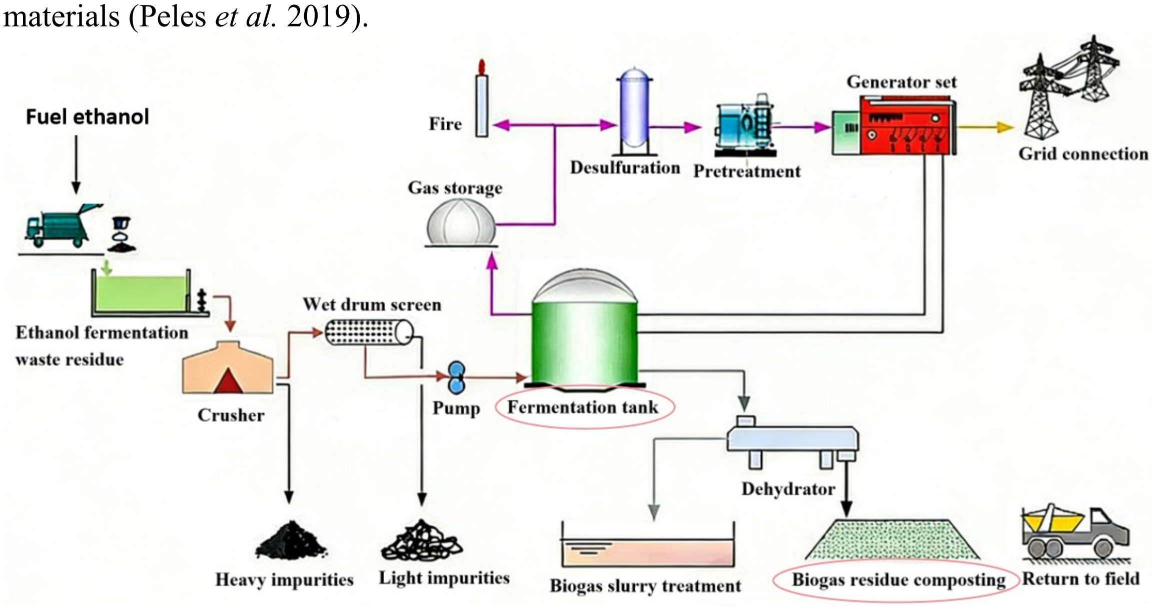


Fig. 2. Process of preparing biogas and detoxification of mycotoxins from whole grain fermentation of waste residues

If discharged or utilized directly without effective treatment, this poses risks to both the environment and food safety. In recent years, the use of anaerobic fermentation technology to treat such organic waste and produce biogas has become a key approach to resource recovery. However, the degradation behavior and transformation mechanisms of various mycotoxins during this process, as well as their impact on the stability of the fermentation system, directly affect the safe utilization of digestate and the economic evaluation of the process (Fig. 2). A comprehensive analysis of the degradation profile of mycotoxins during anaerobic digestion is of critical importance for establishing a scientific risk management system and promoting the healthy development of the circular economy (Pinotti *et al.* 2016).

Degradation Efficiency of Anaerobic Digestion for Different Mycotoxins

The degradation of typical mycotoxins in whole grains fermentation residues have shown that anaerobic digestion is highly effective in removing most of these toxins (Table 2). According to the study by De Gelder *et al*. (2018), batch tests conducted on five common toxins revealed that the degradation rates of aflatoxin B1, ochratoxin A, deoxynivalenol, zearalenone, and T-2 toxin all exceeded 90%. For fumonisin B1, the degradation rate reached 70% under mesophilic digestion conditions and 85% under thermophilic conditions, and the degradation rates for ergot alkaloids were 64% and 98% under mesophilic and thermophilic conditions, respectively (De Gelder *et al.* 2018). Another study further confirmed that when treating contaminated corn feedstock in a continuously operated reactor, the degradation rates of all target mycotoxins exceeded 99% after 1.8 hydraulic retention times (Dereli *et al.* 2014). Mycotoxin levels could be reduced by 27% to 100% during anaerobic digestion, with more thorough degradation observed in heavily contaminated feedstock (Kintl *et al.* 2023). These findings indicate that the anaerobic digestion process generally exhibits high degradation capacity for a wide range of mycotoxins with diverse structures, providing technical feasibility support for the safe treatment of waste residues.

Table 2. Degradation of Mycotoxins during the Preparation of Biogas from Fermentation Residues

Types of Mycotoxins	Degradation Efficiency	Degradation Conditions	Key Influencing Factors	Reference
AFB1	90% - 99%	Batch	Synergistic effects of microbial and physical factors	Cucina and Tacconi (2022)
OTA	> 90%	Batch	Mesophilic or thermophilic anaerobic conditions	Xia *et al*. (2025)
ZEN	100%	Semi-continuous	Mesophilic or thermophilic anaerobic conditions	De Gelder *et al.* (2018)
DON	> 90%	Semi-continuous	Mesophilic or thermophilic anaerobic conditions	De Gelder *et al.* (2018)
T-2	> 90%	Semi-continuous	Mesophilic or thermophilic anaerobic conditions	De Gelder *et al.* (2018)
FB1	Mesophilic digestion: 70%; Thermophilic digestion: 85%	Batch	Temperature: High-temperature (55 °C), Medium-temperature (35 °C)	De Gelder *et al.* (2018)

Factors and Mechanisms Affecting Mycotoxin Degradation

The degradation efficiency of mycotoxins during anaerobic digestion is influenced by a combination of factors, with process parameters and microbial community structure being the key determinants (Giorni *et al.* 2018). Temperature conditions play a significant regulatory role in degradation efficiency. High-temperature digestion typically exhibits higher degradation efficiencies compared to mesophilic digestion, particularly for structurally stable toxins such as fumonisin B1 and ergot alkaloids. Extending the hydraulic retention time facilitates sufficient contact between microorganisms and toxins, thereby enhancing the degree of degradation. High degradation under semi-continuous operating conditions validate this principle. Furthermore, a complex relationship exists between the initial contamination level of the feedstock and degradation efficiency (Gao *et al*. 2023). Kintl *et al*. (2023) found that the degradation of certain toxins was actually more thorough in the moderately contaminated group, whereas the concentration of deoxynivalenol in the low-contamination group even increased by 27.8%. This suggested that the degradation process might be influenced by the interaction of factors such as microbial metabolic activity, the form in which toxins are present, and substrate characteristics (Kintl *et al*. 2023). Regarding the degradation mechanism, anaerobic microbial communities achieve the decomposition or modification of toxin molecules through the secretion of extracellular enzymes, alteration of the local microenvironment, and biotransformation. However, the specific transformation products and changes in their toxicity require further investigation.

The Impact of Mycotoxins on the Operation of Anaerobic Digestion Systems

Mycotoxins not only serve as target pollutants for degradation, but also potentially affect the operational stability of anaerobic fermentation systems (Efremenko *et al.* 2023). In batch experiments, the addition of high concentrations of mycotoxins did not significantly affect biogas or methane production, and process parameters remained stable. This suggests that conventional levels of toxin contamination may not directly inhibit the metabolic activity of anaerobic microorganisms. However, it is important to note that fungal proliferation in feedstock is often accompanied by changes in organic composition, which can indirectly affect gas production performance (Soldano *et al.* 2021). Kintl *et al.* (2023) found that as the degree of fungal contamination increased, the content of neutral detergent fiber, acid detergent fiber, crude fiber, and lignin in the feedstock rose, while soluble sugar content decreased, and these structural changes led to a significant reduction in biogas yield. This suggests that when evaluating the impact of mycotoxins on fermentation systems, the effects of the toxins themselves should be distinguished from the combined effects resulting from feedstock quality deterioration.

Mycotoxin Degradation and Safety Assessment of Digestate and Digested Slurry

The safety of digested sludge and digestate following anaerobic digestion is the ultimate criterion for evaluating the feasibility of this technology (Wang *et al.* 2017). Mycotoxin residues in fully digested material can be reduced to extremely low levels. Continuous operation trials by De Gelder *et al.* (2018) confirmed that no significant concentrations of toxin residues were detected in the digested slurry under stable operating conditions. However, it was worth noting that not all toxins were completely degraded (De Gelder *et al.* 2018). Systematic toxicological evaluations of the residual degradation products are currently lacking, and some transformation products may retain certain biological activities. Furthermore, multiple mycotoxins may coexist in whole-grain fermentation residues, and the potential risks of synergistic effects should not be overlooked. Therefore, relying solely on the degradation rate of the parent toxin as a safety evaluation indicator may have limitations, and establishing a risk assessment system that includes major transformation products is an important direction for future research (Zadeike *et al.* 2021).

DEGRADATION OF MYCOTOXINS DURING THE PRODUCTION OF ORGANIC FERTILIZER FROM WHOLE GRAINS FERMENTATION RESIDUES

Although anaerobic fermented sludge is rich in organic matter and nutrients such as nitrogen, phosphorus, and potassium, it is not yet completely stable, and direct application to soil carries risks. Aerobic composting can convert unstable organic matter in sludge into stable humus through microbial action. At the same time, untreated biogas residue may have plant toxicity (manifested as low seed germination rate) and fungal problems, and there is a higher risk of direct return to the field. The high temperature generated during aerobic composting process kills fungi and insect eggs (Różyło *et al*. 2016). However, during harvesting, storage, or pre-fermentation processing, whole grains are highly susceptible to infection by toxin-producing fungi such as *Fusarium* and *Aspergillus*, which contaminate the raw materials and result in the presence of mycotoxins such as deoxynivalenol, zearalenone, and aflatoxin B_1 in the waste residue. These toxins are chemically stable and highly toxic. If they are not effectively degraded during the organic fertilizer production process, their application to farmland will not only inhibit crop growth and reduce agricultural product quality but may also pose a threat to human and animal health through the food chain (Arata *et al*. 2022). Therefore, elucidating the degradation patterns and mechanisms of mycotoxins during the aerobic composting of whole-grain biogas residues is a scientific prerequisite for ensuring the safe use of organic fertilizers (Jasarevic *et al*. 2025).

Mycotoxin Contamination and the Basic Principles of Composting

Although biogas slurry produced from whole-grain fermentation is rich in organic matter and nutrients, it generally suffers from low decomposition levels and high phytotoxicity, making its direct application to farmland quite risky (Smith *et al.* 2022). When fermentation feedstock is contaminated by mold, biogas slurry may contain residual mycotoxins such as aflatoxin B1, vomitoxin, *etc.* These toxins have stable chemical structures and are difficult to degrade rapidly in the natural environment. If they enter the agricultural ecosystem *via* biogas slurry, they not only inhibit crop growth but may also pose a threat to food safety through the food chain (Arata *et al*. 2022). Aerobic composting, as a mature technology for the stabilization of organic waste, offers a viable technical pathway for the degradation of toxins in digested slurry. During the composting process, microbial communities secrete various extracellular enzymes (such as lignin peroxidase and manganese peroxidase) through metabolic activities. These enzyme systems can attack the toxic groups of mycotoxins, disrupting the molecular structure of the toxins through reactions such as hydroxylation, demethylation, and ring opening, thereby converting them into less toxic or non-toxic metabolites (Qi *et al*. 2022). At the same time, the high-temperature phase of composting (maintained above 55 °C for several days) inherently kills toxin-producing fungi, thereby suppressing the formation of new toxins at the source. Consequently, aerobic composting is regarded as a critical step in achieving the harmless treatment and resource utilization of biogas slurry (Noble *et al*. 2011).

The Key Role of Functional Microorganisms in the Degradation of Mycotoxins

The degradation efficiency of mycotoxins during natural composting is often limited. However, bio-enhancement through the inoculation of specific functional microorganisms can significantly improve toxin removal. The addition of exogenous fungi such as *Paenibacillus* sp. and *Weissella* paramesenteroides can enhance the activity of metabolic pathways related to the biodegradation of exogenous substances in digestate compost, thereby promoting the decomposition and transformation of macromolecular organic matter. The co-composting of moldy feed and crop straw have provided more direct evidence. After 60 d of composting treatment using a composite inoculum of *Weissella paramesenteroides* and *Paenibacillus* sp., the degradation percentages reached 64.5% for aflatoxin B1, 65.0% for T-2 toxin, and 61.3% for ochratoxin A. Meanwhile, zearalenone degradation reached 67.7%, and vomitoxin degradation reached 48.3% (Chen *et al*. 2025). This degradation effect is primarily attributed to two factors: first, the extracellular enzymes – such as cellulase and laccase – secreted by functional strains during the composting process possess non-specific attack capabilities against toxin molecules. Second, the introduction of the composite microbial inoculant optimized the microbial community structure, increasing the relative abundance of functional microorganisms associated with toxin degradation (such as *Bacillus* and *Pseudomonas* species), thereby forming a synergistic microbial ecosystem for degradation. Additionally, composting temperature, lignocellulose content, and humic acid content are key environmental factors influencing microbial community succession, and regulating these parameters can further optimize degradation efficiency (Tao *et al*. 2025).

Factors Affecting Degradation Efficiency and Prospects for Resource Recovery

The degradation efficiency of mycotoxins in digested sludge compost is influenced by multiple factors, and scientifically regulating these factors is key to achieving efficient detoxification. The inoculation with a single microbial strain yields limited degradation results, whereas a composite inoculum consisting of cellulose-degrading bacteria and fermentation-promoting bacteria can produce a synergistic effect, significantly improving toxin removal rates (Wang *et al.* 2024).

For the composting process parameters, temperature control is particularly important to maintain a high-temperature phase above 55 ℃ for 5 to 7 d to kill pathogenic bacteria and toxin-producing fungi without excessively inhibiting the activity of functional microorganisms. Simultaneously, controlling the initial moisture content at 65 to 70% and adjusting the C/N ratio to around 25:1 creates a suitable environment for microbial metabolism (Shen *et al.* 2024).

Regarding substrate characteristics, when the lignocellulose content in biogas slurry was high, adding conditioners such as biochar could improve the permeability of the compost pile, extend the duration of the high-temperature phase, and thereby promote the humification process. From the perspective of resource utilization, composted biogas slurry achieved a seed germination index of over 81.7%, with humus content increasing by more than 15% and total nutrient content significantly rising, indicating that the product possesses good agricultural safety (Maffia *et al.* 2024).

Future research should focus on the screening and domestication of highly efficient degrading strains, the optimization of composite microbial agent formulations, and the elucidation of mycotoxin metabolic pathways during the composting process. This will provide scientific support for establishing a safe technology system for the return of digester residue to farmland, thereby promoting the synergistic development of agricultural waste recycling and agricultural product quality and safety.

FUTURE DIRECTIONS

Research on the degradation of mycotoxins in whole grains during the production of fuel ethanol, biogas, and organic fertilizers is evolving from a focus on "passive removal" toward a future approach centered on "active regulation and synergistic resource conversion." The future trend is to systematically integrate ethanol, biogas, composting and other links, forming a closed-loop system of the entire industry chain with efficient material and energy circulation.

The future efforts should focus on developing engineered strains or enzyme preparations tolerant to high concentrations of toxins and feedback inhibition by metabolites, and deeply integrating them into key process nodes such as ethanol fermentation, biogas methane production, and the humification of organic fertilizers to achieve an integrated approach of "targeted toxin removal-high-efficiency product conversion-safety enhancement."

Concurrently, a comprehensive evaluation system must be established covering the toxicity assessment of degradation intermediates and the safe application of fertilizers throughout the entire chain. By leveraging machine learning and process sensing technologies to enable dynamic optimization, we can promote the synergistic high-value utilization and harmless disposal of byproducts. Ultimately, this will establish a circular economy model centered on "source control—process degradation—end-use safety," providing a systematic solution for the green and low-carbon transformation of the whole-grain deep-processing industry and the safety of agricultural ecosystems.

CONCLUDING STATEMENTS

1. *Limited degradation during ethanol fermentation:* The fermentation pretreatment and distillation processes for fuel ethanol do not fully degrade most mycotoxins; some toxins are transferred to the distiller's grains, increasing the risks associated with subsequent processing.
2. *Turn waste into treasure:* The conversion of waste such as distiller's grains and wastewater generated during ethanol production into energy not only solves the problem of treatment, but also creates new value. Distilled grains are anaerobically digested to produce biogas, which not only treats high concentration organic wastewater but also recovers green energy.

3. *Enhanced biodegradation through composting:* During the aerobic composting of biogas slurry, the synergistic interaction between microbial metabolism and high temperatures further breaks down residual toxins, ensuring the safety of the organic fertilizer product.
4. Coordinated management is required throughout the entire process: Effective toxin reduction and safe resource utilization can only be achieved through process optimization and monitoring across the entire "fermentation-anaerobic digestion-composting" chain.

ACKNOWLEDGMENTS

This research was funded by the Major Science and Technology Projects in Henan Province (261000110700), the Cultivation Project of Tuoxin Team in Henan University of Technology (2024TXTD01), Science and Technology Innovation Leading Talent Program of Henan Province (254200510031), and The Open Research Fund of the Food Laboratory of Zhongyuan (2025410124000444).

REFERENCES CITED

Adácsi, C., Kovács,, S., Pócsi,, I., and Pusztahelyi, T. (2022). "Elimination of deoxynivalenol, aflatoxin B1, and zearalenone by gram-positive microbes (*Firmicutes*)," *Toxins* 14(9), article 591. https://doi.org/10.3390/toxins14090591

Akimsha, R., Basuru, P., Sharmilan, T., and Wanniarachchi, D. (2026). "Advanced applications of electronic nose technology in grain storage and cereal product quality: A comprehensive review of freshness monitoring and mycotoxin detection – A review," *Food Control* 187, article 112093. https://doi.org/10.1016/j.foodcont.2026.112093

Albahri, G., Alyamani A. A., Badran, A., Hijazi, A., Nasser, M., Maresca, M., and Baydoun, E. (2023). "Enhancing essential grains yield for sustainable food security and bio-safe agriculture through latest innovative approaches," *Agronomy* 13(7), article 1709. https://doi.org/10.3390/agronomy13071709

Anukul, N., Maneeboon, T., Roopkham, C., Chuaysrinule, C., and Mahakarnchanakul, W. (2014). "Fumonisin and T-2 toxin production of *Fusarium* spp. isolated from complete feed and individual agricultural commodities used in shrimp farming," *Mycotoxin Research* 30, 9-16. https://doi.org/10.1007/s12550-013-0182-y

Arata, G. J., Martínez, M., Elguezábal, C., Rojas, D., Cristos, D., Dinolfo M. I., and Arata, A. F. (2022). "Effects of sowing date, nitrogen fertilization, and *Fusarium graminearum* in an Argentinean bread wheat: Integrated analysis of disease parameters, mycotoxin contamination, grain quality, and seed deterioration," *Journal of Food Composition and Analysis* 107, article 104364. https://doi.org/10.1016/j.jfca.2021.104364

Bereda, G. (2025). "Toxicological impacts, mitigation, and policy strategies of food contaminants: A global perspective and comprehensive narrative review." *Public, Environmental and Occupational Health* 10, article 2196. https://doi.org/10.20944/preprints202510.2196.v1

Bernhoft, A., Wang, J., and Leifert, C. (2022). "Effect of organic and conventional cereal production methods on fusarium head blight and mycotoxin contamination levels," *Agronomy* 12(4), article 797. https://doi.org/10.3390/agronomy12040797

Berwian G. F., Rempel, A., Garda-Buffon, J., and Colla, L. M. (2024). "Use of residual barley to bioethanol production: Valoration, mycotoxins decontamination and feed production," *Bioresource Technology Reports* 26, article 101878. https://doi.org/10.1016/j.biteb.2024.101878

Bowers, E. L., and Munkvold, G. P. (2014). "Fumonisins in conventional and transgenic, insect-resistant maize intended for fuel ethanol production: Implications for fermentation efficiency and DDGS co-product quality," *Toxins*, 6(9), 2804-2825. https://doi.org/10.3390/toxins6092804

Chang, M., Zhu, T., Xiao, T., Wang, J., Wang, N., Song, Y., and Wang, Y. (2024). "Novel process for organic wastewater treatment using aerobic composting technology: Shifting from pollutant removal towards resource recovery," S*cience of The Total Environment* 913, article 169522. https://doi.org/10.1016/j.scitotenv.2023.169522

Chavan, S., Mitra, D., and Ray A. (2024). "Harnessing rice husks: Bioethanol production for sustainable future," *Current Research in Microbial Sciences* 7, article 100298. https://doi.org/10.1016/j.crmicr.2024.100298

Chlebicz, A., and Śliżewska, K. (2020). "*In vitro* detoxification of aflatoxin B1, deoxynivalenol, fumonisins, T-2 toxin and zearalenone by probiotic bacteria from genus *Lactobacillus* and *Saccharomyces cerevisiae* yeast," *Probiotics and Antimicrobial Proteins* 12, 289-301. https://doi.org/10.1007/s12602-018-9512-x

Cucina, M., and Tacconi, C. (2022). "Recovery of energy and nutrients from mycotoxin-contaminated food products through biological treatments in a circular economy perspective: A review," *Agronomy* 12(12), article 3198. https://doi.org/10.3390/agronomy12123198

Ćurčić, S., Milićević, D., Kilibarda, N., and Peulić, A. (2025). "Assessing biogas production potential from organic waste and livestock byproducts in a Serbian municipality: Implications for sustainable food systems," *Sustainability* 17(7), article 3144. https://doi.org/10.3390/su17073144

De Gelder, L., Audenaert, K., Willems, B., Schelfhout, K., De Saeger, S., and De Boevre, M. (2018). "Processing of mycotoxin contaminated waste streams through anaerobic digestion," *Waste Management* 72, 122-128. https://doi.org/10.1016/j.wasman.2017.09.039

Dereli R., K., van der Zee F. P., Heffernan, B., Grelot, A., and van Lier, J. B. (2014). "Effect of sludge retention time on the biological performance of anaerobic membrane bioreactors treating corn-to-ethanol thin stillage with high lipid content," *Water Research* 49, 453-464. https://doi.org/10.1016/j.watres.2013.10.035

Favaro, L., Cagnin, L., Basaglia, M., Pizzocchero, V., van Zyl, W. H., and Casella, S. (2017). "Production of bioethanol from multiple waste streams of rice milling," *Bioresource Technology* 244(1), 151-159. https://doi.org/10.1016/j.biortech.2017.07.108

Ferdous, Z., Ullah, H., Datta, A., Attia, A., Rakshit, A., and Molla, S. H. (2020). "Application of biogas slurry in combination with chemical fertilizer enhances grain yield and profitability of maize (*Zea Mays* L.)," *Communications in Soil Science and Plant Analysis* 51(19), 2501-2510. https://doi.org/10.1080/00103624.2020.1844728

Ferrara, M., Haidukowski, M., D'Imperio, M., Parente, A., De Angelis, E., Monaci, L., Logrieco, A. F., and Mule, G. (2021). "New insight into microbial degradation of mycotoxins during anaerobic digestion," *Waste Management* 19, 215-225. https://doi.org/10.1016/j.wasman.2020.09.048

Gao, C., El-Sawah A. M., Ali, D. F. I., Alhaj Hamoud, Y., Shaghaleh, H., and Sheteiwy, M. S. (2020). "The integration of bio and organic fertilizers improve plant growth, grain yield, quality and metabolism of hybrid maize (*Zea mays* L.)," *Agronom*y 10(3), article 319. https://doi.org/10.3390/agronomy10030319

Gavahian, M., Mathad G. N., Oliveira C. A.F., and Khaneghah, A. M. (2021). "Combinations of emerging technologies with fermentation: Interaction effects for detoxification of mycotoxins?," *Food Research International* 141, article 110104. https://doi.org/10.1016/j.foodres.2021.110104

Giacomini, R. X., Acosta, E. R., Cerqueira, M. B. R., Primel, E. G., and Garda-Buffon, J. (2023). "Alcoholic fermentation as a strategy to mitigate pesticides and mycotoxins," *Food Bioprocess Technology* 16, 2315-2327. https://doi.org/10.1007/s11947-023-03070-9

Giorni, P., Pietri, A., Bertuzzi, T., Soldano, M., Piccinini, S., Rossi, L., and Battilani, P. (2018). "Fate of mycotoxins and related fungi in the anaerobic digestion process," *Bioresource Technology* 265, 554-557. https://doi.org/10.1016/j.biortech.2018.05.077

Green, D. I. G., Agu, R. C., Bringhurst, T. A. Brosnan, J. M., Jack, F. R., and Walker, G. M. (2015). "Maximizing alcohol yields from wheat and maize and their co-products for distilling or bioethanol production," *Journal of the Institute of Brewing* 121(3), 332-337. https://doi.org/10.1002/jib.236

Gurikar, C., Shivaprasad, D. P., Sabillón, L., Gowda, N. A. N., and Siliveru, K. (2023). "Impact of mycotoxins and their metabolites associated with food grains," *Grain & Oil Science and Technology* 6(1), 1-9. https://doi.org/10.1016/j.gaost.2022.10.001

Hao, J., Yang, M., Dabbour, M., Mintah, B. K., Dai, C., Zhang, R., Zhang, Z., Ma, H., and He, R. (2025). "Enhancing ethanol tolerance and metabolic activity of *Saccharomyces cerevisiae* during rice fermentation by fixed-frequency ultrasound," *Food Research International* 218, article 116892. https://doi.org/10.1016/j.foodres.2025.116892

Hoang, T. D., and Nghiem, N. (2021). "Recent developments and current status of commercial production of fuel ethanol," *Fermentation* 7(4), article 314. https://doi.org/10.3390/fermentation7040314

Jasarevic, M., Rodriguez, C. M., Scialò, G., De Santis, B., Debegnach, F., Palchetti, A., D'Ambrosio, L., Caprai, E., Sonfack, G. M., Mancinelli, R., Catalani, A., and Chilosi, G. (2025). "Durum wheat kernel contamination by mycotoxigenic fungi and mycotoxins as affected by soil tillage and fertilization management in a Mediterranean environment," *Journal of Plant Pathology* 107, 1363-1376. https://doi.org/10.1007/s42161-025-01897-z

Ji, C., Fan, Y., and Zhao, L. (2016). "Review on biological degradation of mycotoxins," *Animal Nutrition* 2(3), 127-133. https://doi.org/10.1016/j.aninu.2016.07.003

Juodeikiene, G., Basinskiene, L., Vidmantiene, D., Bartkiene E. (2009). "Reduction of deoxynivalenol (DON) using xylanolytic enzymes during alcoholic fermentation of Fusarium contaminated wheat," *First International Conference Sustainable Postharvest and Food Technologies-INOPTEP 2009 and XXI National Conference Processing and Energy in Agriculture-PTEP* 13(2), 107-110

Keller, L., Abrunhosa, L., Keller, K., Rosa, C. A., Cavaglieri, L., and Venâncio, A. (2015). "Zearalenone and its derivatives α-Zearalenol and β-Zearalenol decontamination by *Saccharomyces cerevisiae* strains isolated from bovine forage," *Toxins* 7(8), 3297-3308. https://doi.org/10.3390/toxins7083297

Khatibi, P. A., Montanti, J., Nghiem, N. P., Hicks, K. B., Berger, G., Brooks, W. S., Griffey, C. A., and Schmale III, D. G. (2011). "Conversion of deoxynivalenol to 3-acetyldeoxynivalenol in barley-derived fuel ethanol co-products with yeast expressing trichothecene 3-O-acetyltransferases," *Biotechnol. Biofuels* 4, article 26. https://doi.org/10.1186/1754-6834-4-26

Kintl, A., Vítěz, T., Huňady, I., Sobotková, J., Hammerschmiedt, T., Vítězová, M., Brtnický, M., Holátko, J., and Elbl J. (2023). "Mycotoxins in maize silage and their degradation during anaerobic digestion," *Bioengineering* 10(12), article 1387 https://doi.org/10.3390/bioengineering10121387

Kłosowski, G., Koim-Puchowska, B., Dróżdż-Afelt, J., and Mikulski, D. (2023). "The reaction of the yeast *Saccharomyces cerevisiae* to contamination of the medium with aflatoxins B2 and G1, ochratoxin A and zearalenone in aerobic cultures," *International Journal of Molecular Sciences*, 24(22), article 16401. https://doi.org/10.3390/ijms242216401

Li, L., Hu, M., Gul, S., Ma, Y., Dai, X., Hao, Q., Zhang, J., Huang, W., and Wang, Y. (2026). "Functionalized nanoplastics alter physiology and toxin production in *Alexandrium pacificum* through surface charge effects," *Sustainable Horizons* 17, article 100171. https://doi.org/10.1016/j.horiz.2025.100171

Lillehoj, E.B., Lagoda, A., and Maisch, W. F. (1979). "The fate of aflatoxin in naturally contaminated corn during the ethanol fermentation," *Canadian Journal of Microbiology* 25(8), 911-914. https://doi.org/10.1139/m79-135

Liu, L., Xie, M., and Wei, D. (2022). "Biological detoxification of mycotoxins: Current status and future advances," *International Journal of Molecular Sciences* 23(3), article 1064. https://doi.org/10.3390/ijms23031064

Loi, M., Fanelli, F., Liuzzi, V. C., Logrieco, A. F., and Mulè, G. (2017). "Mycotoxin biotransformation by native and commercial enzymes: Present and future perspectives," *Toxins* 9(4), article 111. https://doi.org/10.3390/toxins9040111

Maffia, A., Marra, F., Canino, F., Battaglia, S., Mallamaci, C., Oliva, M., and Muscolo, A. (2024). "Humic substances from waste-based fertilizers for improved soil fertility," *Agronomy* 14(11), article 2657. https://doi.org/10.3390/agronomy14112657

Marzano, M., Calasso, M., Caponio G.R., Celano, G., Fosso, B., De Palma, D., Vacca, M., Notario, E., Pesole, G., De Leo, F., and De Angelis, M. (2022). "Extension of the shelf-life of fresh pasta using modified atmosphere packaging and bioprotective cultures," *Frontiers in Microbiology* 13, article 1003437. https://doi.org/10.3389/fmicb.2022.1003437

Mishra, S., Lin, Z., Pang, S., Zhang, W., Bhatt, P., and Chen, S. (2021). "Recent advanced technologies for the characterization of xenobiotic-degrading microorganisms and microbial communities," *Frontiers in Bioengineering and Biotechnology* 9, article 632059. https://doi: 10.3389/fbioe.2021.632059

Murtaza, B., Wang, L., Li, X., Ali, A., Haq, S. U., Li, J., and Xu, Y. (2024). "Novel *lactobacillus consortium* for effective zearalenone adsorption and biodegradation," *International Biodeterioration & Biodegradation* 194, article 105889. https://doi.org/10.1016/j.ibiod.2024.105889

Murtaza, B., Guo, L., Wang, L., Li, X., Ali, A., Saleemi, M. K., Khatoon, A., Haq, S. U., Jin, B., Li, J., and Xu, Y. (2025). "Mycotoxin detection in corn and distillers dried grains for food security," *Renewable and Sustainable Energy Reviews* 210, article 115194. https://doi.org/10.1016/j.rser.2024.115194

Nabgan, M., Shariatifar, N., and Zeinali, T. (2025). "Comparative investigation of Mycotoxin detoxification mechanisms by lactic acid bacteria (*Lactobacillus* species) and non-lactic acid bacteria," *Journal of Food Measurement and Characterization* 19, 3839-3866 (2025). https://doi.org/10.1007/s11694-025-03259-w

Noble, R., Dobrovin-Pennington, A., Pietravalle, S., Weekes, R., and Henry, C. M. (2011). "Indicator organisms for assessing sanitization during composting of plant wastes," *Waste Management* 31(8), 1711-1718. https://doi.org/10.1016/j.wasman.2011.04.007

Okoye, C. O., Ezenwanne, B. C., Olalowo, O. O., Ajanwachukwu, O. J., and Chukwudozie, K. I. (2026). "Microbial-mycotoxin interactions in food: A review of ecotoxicological implications and omics approaches for understanding detoxification mechanisms," *Food Microbiology* 135, article 104955. https://doi.org/10.1016/j.fm.2025.104955

Ouyang, B., Zhang, W., Guang, C., Xu, W., and Mu, W. (2024). "Opportunities and challenges in developing promising mycotoxin-degrading enzymes with high thermostability and strong pH activity/stability," *Food Bioscience* 62, article 105239. https://doi.org/10.1016/j.fbio.2024.105239

Pande, A., Paliwal, J., Jian, F., and Bakker, M. G. (2025). "Mechanisms and application of mycotoxin decontamination techniques in stored grains," *Journal of Stored Products Research* 111, article 102486. https://doi.org/10.1016/j.jspr.2024.102486

Paneru, D., Sharma M. K., Shi, H., Goo, D., Choppa V. S. R., Gyawali, I., Shanmugasundaram, R., and Kim, W. K. (2025). "Effects of deoxynivalenol contaminated corn distiller's dried grains with solubles on growth performance, body composition, immunological response, and gastrointestinal health in young pullets," *Poultry Science* 104(1), article 104611. https://doi.org/10.1016/j.psj.2024.104611

Peles, F., Sipos, P., Győri, Z., Pfliegler W. P., Giacometti, F., Serraino, A., Pagliuca, G., Gazzotti, T., and Pócsi, I. (2019). "Adverse effects, transformation and channeling of aflatoxins into food raw materials in livestock. *Frontiers in Microbiology* 10, article 2861. https://doi.org/10.3389/fmicb.2019.02861

Pinotti, L., Ottoboni, M., Giromini, C., Dell'Orto, V., C and heli, F. (2016). "Mycotoxin contamination in the EU feed supply chain: A focus on cereal byproducts," *Toxins* 8(2), article 45. https://doi.org/10.3390/toxins8020045

Qi, C., Yin, R., Gao, X., Chen, J., Wang, R., Xu, Z., Luo, W., Li, G., and Li, Y. (2022). "Development of solid-state anaerobic digestion and aerobic composting hybrid processes for organic solid waste treatment and resource recovery: A review," *Current Pollution Reports* 8, 221-233 https://doi.org/10.1007/s40726-022-00223-w

Różyło, K., Gawlik-Dziki, U., Świeca, M., Różyło, R., and Pałys, E. (2016). "Winter wheat fertilized with biogas residue and mining waste: Yielding and the quality of grain," *Journal of the Science of Food and Agriculture* 96(10), 3454-3461. https://doi.org/10.1002/jsfa.7528

Sadhasivam, S., Britzi, M., Zakin, V., Kostyukovsky, M., Trostanetsky, A., Quinn, E., and Sionov, E. (2017). "Rapid detection and identification of mycotoxigenic fungi and mycotoxins in stored wheat grain," *Toxins* 9(10), article 302. https://doi.org/10.3390/toxins9100302

Santos R. R., Oosterveer-van der Doelen M. A. M., Tersteeg-Zijderveld M. H. G., Molist, F., Mézes, M., and Gehring, R. (2021). "Susceptibility of broiler chickens to eeoxynivalenol exposure via artificial or natural dietary contamination," *Animals* 11(4), article 989. https://doi.org/10.3390/ani11040989

Shen, B., Zheng, L., Zheng, X., Yang, Y., Xiao, D., Wang, Y., Sheng, Z., and Ai, B. (2024). "Insights from meta-analysis on carbon to nitrogen ratios in aerobic composting of agricultural residues," *Bioresource Technology* 413, article 131416. https://doi.org/10.1016/j.biortech.2024.131416

Shi, H., Schwab, W., and Yu, P. (2019). "Natural occurrence and co-contamination of twelve mycotoxins in industry-submitted cool-season cereal grains grown under a low heat unit climate condition," *Toxins* 11(3), article 160. https://doi.org/10.3390/toxins11030160

Shi, J., Mwabulili, F., Xie, Y., Yang, Y., Sun, S., Li, Q., Ma, W., and Jia, H. (2024). "Characterization, structural analysis, and thermal stability mutation of a new zearalenone-degrading enzyme mined from *Bacillus subtilis*," *Journal of Agriculturaland Food Chemistry* 72 (6), 3025-3035. https://doi.org/10.1021/acs.jafc.3c06767

Smith, C., Van Haute, M. J., Xian, Y., Segura Munoz, R. R., Liu, S., Schmaltz, R. J., Ramer-Tait, A. E., and Rose, D. J. (2022). "Carbohydrate utilization by the gut microbiome determines host health responsiveness to whole grain type and processing methods," *Gut Microbes* 14(1), article 2126275. https://doi.org/10.1080/19490976.2022.2126275

Soldano, M., Pietri, A., Bertuzzi, T., Fabbri, C., Piccinini, S., Gallucci, F., and Aureli, G. (2021). "Anaerobic digestion of mycotoxin-contaminated wheat: Effects on methane yield and contamination level," *BioEnergy Research* 14, 313-321. https://doi.org/10.1007/s12155-020-10161-4

Sosa, M. A., Chovau, S., Van der Bruggen, B., and Espinosa, J. (2013). "Ethanol production from corn contaminated with Fumonisins: A preliminary economic analysis including novel processing alternatives," *Industrial & Engineering Chemistry Research* 55(22), 7504-7513. https://doi.org/10.1021/ie303040p

Sun, X., Devi, N. D., Urriola, P. E., Tiffany, D. G., Jang, J., Shurson, G. G., and Hu, B. (2021). "Feeding value improvement of corn-ethanol co-product and soybean hull by fungal fermentation: Fiber degradation and digestibility improvement," *Food and Bioproducts Processing* 130, 143-153. https://doi.org/10.1016/j.fbp.2021.09.013

Tao, W., Deng, Y., Li, K., Shen, B., and Wei, Z. (2025). "Mechanistic insights into humic acid formation from lignocellulosic waste via aerobic composting: A review," *International Journal of Biological Macromolecules* 330(4), article 148283. https://doi.org/10.1016/j.ijbiomac.2025.148283

Tournas, V. H., and Niazi, N. S. (2018). "Potentially toxigenic fungi from selected grains and grain products," *Journal of Food Safety* 38(1), article e12422. https://doi.org/10.1111/jfs.12422

Trakselyte-Rupsiene, K., Juodeikiene, G., Hajnal, E. J., Bartkevics, V., Pugajeva, I., Klupsaite, D., Cernauskas, D., Lele, V., Zadeike, D., and Bartkiene, E. (2022). "Challenges of *Lactobacillus* fermentation in combination with acoustic screening for deoxynivalenol and deoxynivalenol conjugates reduction in contaminated wheat-based products," *Food Control* 134, article 108699. https://doi.org/10.1016/j.foodcont.2021.108699

Vidal, A., Sanchis, V., Ramos, A. J., and Marín, S. (2017). "Effect of xylanase and α-amylase on DON and its conjugates during the breadmaking process," *Food Research International* 101, 139-147. https://doi.org/10.1016/j.foodres.2017.08.021

Wall-Martínez H. A., Pascari, X., Bigordà, A., Ramos A. J., Marín, S., and Sanchis, V. (2019). "The fate of *Fusarium mycotoxins* (deoxynivalenol and zearalenone) through wort fermenting by *Saccharomyces* yeasts (*S. cerevisiae* and *S. pastorianus*)," *Food Research International* 126, article 108587. https://doi.org/10.1016/j.foodres.2019.108587

Wang, M., Zhang, Y., Yan, S., Yi, B., Niu, W., and Yuan, Q. (2017). "Enhanced biogas yield of chinese herbal medicine extraction residue by hydrothermal pretreatment," *BioResources* 12(3), 4627-4638. https://doi.org/10.15376/biores.12.3.4627-4638

Wang, Y., Yang, L., Xu, J., Xin, F., and Jiang, L. (2023). "Applications of synthetic microbial consortia in biological control of mycotoxins and fungi," *Current Opinion in Food Science* 53, article 101074. https://doi.org/10.1016/j.cofs.2023.101074

Wang, L., Li, Y., and Li, X. (2024). "Microbe-aided thermophilic composting accelerates manure fermentation," *Frontiers in Microbiology* 15, article 1472922. https://doi:10.3389/fmicb.2024.1472922

Wang, J., Ma, T., Xie, Y., Li, K., Luo, C., Teng, C., Yi, B., Chen, L., and Zhang, H. (2025). "A cellulose-degrading *Bacillus altitudinis* from Tibetan pigs improved the in vitro fermentation characteristics of wheat bran," *Computational and Structural Biotechnology Journal* 27, 1233-1243. https://doi.org/10.1016/j.csbj.2025.03.025

Wei, Z., Huang, J., Yang, C., Xu, Y., Shen, Q., and Chen, W. (2015). "Screening of suitable carriers for *Bacillus amyloliquefaciens* strain QL-18 to enhance the biocontrol of tomato bacterial wilt," *Crop Protection* 75, 96-103. https://doi.org/10.1016/j.cropro.2015.05.010.

Xia, W., Zhu N., Mei, J., Peng, Y., Song, F., Ding, S., Li, F., and Zhou, X. (2025). "Biocatalytic detoxification of ochratoxins A/B by a fungal dye-decolorizing peroxidase: mechanistic insights and toxicity assessment," *Toxins* 17(9), article 438. https://doi.org/10.3390/toxins17090438

Xu, R., Pu, Z., Han, S., Yu, H., Guo, C., Huang, Q., and Zhang, Y. (2025). "Managing forage for grain: Strategies and mechanisms for enhancing forage production to ensure feed grain security," *Journal of Integrative Agriculture* 24(6), 2025-2034. https://doi.org/10.1016/j.jia.2024.11.017

Yao, J., Ouyang, B., Xu, W., Xie, Y., and Mu, W. (2026). "An overview of the physical, chemical and biological strategies for the removal of emerging mycotoxins: Recent advances and future perspectives," *Food Control* 181, article 111700. https://doi.org/10.1016/j.foodcont.2025.111700

You, Y., Qiu, Y., Xu, H., He, R., Zhang, L., Wang, Z., and Xia, Y. (2024). "Effective and food-grade detoxification of multiple mycotoxins using yeast expressed manganese peroxidases," *Food Bioscience* 59, article 103886. https://doi.org/10.1016/j.fbio.2024.103886

Zadeike, D., Vaitkeviciene, R., Bartkevics, V., Bogdanova, E., Bartkiene, E., Lele, V., Juodeikiene, G., Cernauskas, D., and Valatkeviciene, Z. (2021). "The expedient application of microbial fermentation after whole-wheat milling and fractionation to mitigate mycotoxins in wheat-based products," *LWT* 137, article 110440. https://doi.org/10.1016/j.lwt.2020.110440

Zhang, H., Dong, M., Yang, Q., Apaliya, M. T., Li, J., and Zhang, X. (2016). "Biodegradation of zearalenone by *Saccharomyces cerevisiae*: Possible involvement of ZEN responsive proteins of the yeast," *Journal of Proteomics* 143, 416-423. https://doi.org/10.1016/j.jprot.2016.04.017

Zhang, L., Shen, X., Wang, Z., Peng, Y., Yang, J., Cai, Y., Wang, S., Xu, J., and Ying, H. (2026). "Production of high-nutrient protein sources by pre-secondary solid-state fermentation of functional microbiota (Pre-Sec-SSF-FM) from dehulled Chinese distillers grains," *Journal of Biotechnology* 410, 23-32. https://doi.org/10.1016/j.jbiotec.2025.11.012

Article submitted: April 12, 2026; Peer review completed: August 7, 2026; Revised version received and accepted: August 30, 2026; Published: September 10, 2026.
DOI: 10.15376/biores.21.4.Wang