Review

Microbiological Decontamination of Mycotoxins: Opportunities and Limitations

Małgorzata Piotrowska

Faculty of Biotechnology and Food Sciences, Institute of Fermentation Technology and Microbiology, Lodz University of Technology, Wólczańska 171/173, 90-530 Lodz, Poland; malgorzata.piotrowska@p.lodz.pl

Abstract: The contamination of food and feeds with mycotoxins poses a global health risk to humans and animals, with major economic consequences. Good agricultural and manufacturing practices can help control mycotoxin contamination. Since these actions are not always effective, several methods of decontamination have also been developed, including physical, chemical, and biological methods. Biological decontamination using microorganisms has revealed new opportunities. However, these biological methods require legal regulations and more research before they can be used in food production. Currently, only selected biological methods are acceptable for the decontamination of feed. This review discusses the literature on the use of microorganisms to remove mycotoxins and presents their possible mechanisms of action. Special attention is given to Saccharomyces cerevisiae yeast and lactic acid bacteria, and the use of yeast cell wall derivatives.

Keywords: mycotoxins; decontamination; adsorption; detoxification; microorganisms; lactic acid bacteria; yeasts

Key Contribution: The use of microorganisms or their enzymes to detoxify mycotoxins generates new possibilities in food and feed production. Lactic acid bacteria and certain species of yeast able to decontaminate mycotoxins could obtain consumer acceptance for use in the production of fermented foods.

1. Introduction

Mycotoxins are secondary metabolites of fungi that contaminate both plant raw materials and products of plant and animal origin. They can be produced at any stage of the food chain, mainly by fungi belonging to the genera Aspergillus, Penicillium, Fusarium, Byssochlamys, or Alternaria. Currently, more than 400 compounds are identified as mycotoxins. Most scientific attention has been focused on only a few, due to their frequency and toxic properties. The most important mycotoxins are aflatoxins (AFs), ochratoxin A (OTA), patulin (PAT), citrinin (CIT), Fusarium toxins represented by fumonisins (FUM), deoxynivalenol (DON) and their derivatives, zearalenone (ZEN), T-2 and HT-2 toxins (T-2, HT-2), Alternaria toxins, such as alternariol (AOH), alternariol methyl ether (AME), tenuazonic acid (TeA), and Claviceps ergot alkaloids [1,2].

The main source of human exposure to mycotoxins is food, including not only contaminated food products of plant origin (the primary route), but also contaminated animal tissues (meat, milk, and eggs) derived from animals fed with contaminated fodder. Prolonged exposure to small doses of mycotoxins causes poisoning of various forms, called mycotoxicosis, which may be acute or chronic. Humans and animals are exposed to various types of mycotoxins simultaneously, which may result in antagonistic, additive, or synergistic effects [3]. Mycotoxins have numerous effects on human and animal bodies, causing liver and kidney damage, as well as interfering with the functioning of the digestive tract and the immune system. They may exhibit carcinogenic, mutagenic, cytotoxic, teratogenic, neurotoxic, or estrogenic properties [2].
To protect public health in the European Union (EU), the maximum levels of the most toxicologically important mycotoxins permitted in foodstuffs have been established based on the opinions of the European Food Safety Authority (EFSA). EU Regulation 1881/2006 and its amendments (1126/2007, 105/2010, 165/2010, 594/2012 1058/2012, 2015/1137, and 2019/1901) established the maximum acceptable limits for AFs (in nuts, dried fruits, cereals and cereal products, spices, and milk), ochratoxin A (in cereals and cereal products, dried fruits, coffee, grape juice and wine, spices, licorice), patulin (in fruit juices, spirit drinks, cider), fumonisins, deoxynivalenol, zearalenone (in cereals and cereal products, maize and maize-based products, pasta, bread), and citrinin (in food supplements based on rice fermented with Monascus purpureus) [4–11]. Similar regulations, though not covering such a wide range of mycotoxins and product categories, are in force in the USA, Canada, Australia, Japan, China, and other countries, as well as in Codex Alimentarius standards. Maximum acceptable limits also apply to feed—e.g., in EU regulations such as Commission Recommendation 2006/576 [12].

Most review publications on the scale of contamination cite Food and Agriculture Organization of the United Nations (FAO) data from 25 years ago that “up to 25% of world food crops are significantly contaminated with mycotoxins” [13]. According to more recent data published by Eskola et al. [14], the number of tested samples that exceed acceptable mycotoxin levels in the European Union (EU) are in line with the FAO estimate.

The scale of mycotoxin contamination in foodstuffs analyzed during official food control is reflected in the number of notifications issued by the Rapid Alert System for Food and Feed (RASFF), which is a platform for exchanging information about foods and feeds that may pose a hazard to consumers in Europe. In recent years (since 2015), the RASFF system has registered over 500 notifications of excessive mycotoxin levels in food per year (Figure 1). In 2021, in the period before September, there were 294 notifications, including 16% alert and 8% information notifications. Most notifications were issued by border control (76%). Nuts, nut products, and seeds were the main product categories exposed to contamination (62%).

![Figure 1. RASFF notifications of excessive levels of mycotoxins from 2015 to 2021. Detailed data on the type of notification, mycotoxins, and products category relate to 2021.](image-url)
The scale of the problem appears even greater when we consider levels of mycotoxins in plant materials and food products that are above the limits of detection (LODs) by analytical methods. Not all collected data are published and disseminated by the FAO, World Health Organization (WHO), or EFSA [14]. However, according to Lee and Ryu, 61% of unprocessed food-grade cereals tested worldwide between 2006 and 2016 were contaminated with fumonisins. The incidence of contamination varied from 39% in Europe to 95% in America [15]. The most up-to-date reports on feed contamination are provided by Biomin (Austria). According to their data for the third quarter of 2020 to the second quarter of 2021, the proportions of feed contaminated with mycotoxins were as follows: OTA—9%, T-2—11%, AFs—14%, ZEN—49%, FUM—49%, DON—54%. It should be emphasized that 55% of the feeds were contaminated with more than one mycotoxin, which may increase their toxic effects [16]. The data from Europe are the most complete. However, this information only includes mycotoxins covered by EU regulations—i.e., AFs, OTA, PAT, ZEA, DON, and FUM. The data do not take into account other toxic metabolites, such as Alternaria toxins and sterigmatocystin, or masked mycotoxins not detected by routine methods [17].

In addition to its negative impact on human and animal health, mycotoxin contamination has global economic consequences. For this reason, minimizing mycotoxin contamination has become a priority for scientists and organizations including the WHO, FAO, and EFSA.

2. Mycotoxin Control Strategies

There are two strategies for the control of mycotoxin contamination (Figure 2): prevention strategies (white boxes) and decontamination strategies (gray boxes). These strategies can be employed at different stages of the production process, often classified as pre-harvest and post-harvest (above and under the dotted line, respectively).

![Figure 2. Mycotoxin control strategies.](image)

Pre-harvest actions include: the selection of varieties or hybrids resistant to fungal infections and insect pests; minimizing the exposure of plants to stress (drought); careful use of insecticides and herbicides; crop rotation; timely harvest; good soil management to remove, destroy, or bury infected harvest residues. Guidelines for the application of appropriate preventive measures are presented in EU Regulation 1881/2006 and EU
Post-harvest methods to prevent the growth of toxicogenic fungi include storage of crops under conditions of appropriate humidity and temperature, or the use of chemical fungicides. If, despite these methods, the products are contaminated with mycotoxins, treatments may be applied to reduce levels of mycotoxins. These include traditional and innovative physical methods (e.g., sorting, thermal treatment, UV radiation, cold plasma, electron beam irradiation, pulsed electric field, adsorbents), as well as chemical methods (addition of oxidants such as hydrogen peroxide, sulfur dioxide, sodium hypochlorite, ozone, or ammonia) [19–21].

However, some of these methods are not applicable in practice, mainly due to the risk of creating toxic residues or affecting the nutritional value and organoleptic properties of the purified products [20]. Moreover, there are currently no legal regulations regarding decontamination of food. According to Regulation 1881/2006, foodstuffs that do not comply with accepted maximum levels of toxins should not be used as food ingredients, nor mixed with other foodstuffs, and should not be deliberately detoxified using chemical treatments. The presence of contaminants in food must be reduced as much as possible by Good Manufacturing Practice (GMP), Good Agriculture Practices (GAP), and the application of Hazard Analysis and Critical Points (HACCP). Sorting or other physical treatment methods make it possible to reduce the AF content in groundnuts, nuts, dried fruit, and cereals [11]. The regulations do not mention biological methods of decontamination.

3. Background

The subject of reducing the number of mycotoxins in food and feed is of great interest to scientists. Searching the Web of Science Core Collection for the terms (“mycotoxins” OR “mycotoxin”) AND (“degradation” OR “biodegradation” OR “detoxification” OR “biodetoxification” OR “binding” OR “control” OR “adsorption” OR “elimination” OR “decreasing” OR “minimizing” OR “inactivation” OR “mitigation” OR “transformation” OR “biotransformation” OR “decontamination”) yields 8854 publications from 1990 to the present day. The majority of these publications are original articles. The number of review articles is growing, but they still constitute only 9% of the total number of articles (Figure 3).

Figure 3. Number of publications on mycotoxin biodegradation from 1990 to 2021, based on the results of searching the Web of Science Core Collection (total = 8854).
A preliminary review of the literature published in the years 1990–2021, using the terms “(bio)degradation”, “(bio)detoxification”, “(bio)transformation”, “decontamination”, “binding”, “control”, “adsorption”, “elimination”, “decreasing”, “minimizing”, “inactivation”, and “mitigation” in combination with “mycotoxins”, identified almost 9000 articles, book chapters, and conference papers in scientific databases (Scopus, Science Direct, Web of Science). The search terms were included in the titles, keywords, and abstracts. Articles published in languages other than English were excluded, as were articles that were unavailable as full texts, and conference papers that had not been peer-reviewed.

In total, 136 scientific papers were selected for discussion in this literature review, of which 66% were published in the years 2010–2021, 28% in 2000–2009, 4% in 1990–2000, and 1% before the 1990s. Thirteen law regulations and one web page were also reviewed. The selected publications were used to answer the following questions: (1) What is the level of research interest in this topic, in terms of the number of publications? (2) What is the current situation, in terms of mycotoxin contamination of food and feed products? (3) What trends can be identified in research on mycotoxin decontamination? (4) Which microorganisms show the greatest potential for use as decontaminants? (5) What are their mechanisms of decontamination? (6) Which methods can be applied in practice?

4. Microbiological Methods of Decontamination

The idea of using microorganisms to remove mycotoxins appeared as early as the 1960s. Ciegler et al. [22] reviewed microorganisms in terms of their ability to degrade aflatoxins (AFs). They found that some molds, including \textit{Aspergillus niger}, \textit{Aspergillus parasiticus}, \textit{Aspergillus terreus}, \textit{Aspergillus luchuensis}, \textit{Penicillium reistrickii}, as well as \textit{Flavobacterium aurantiacum} (now \textit{Rhodococcus corynebacterioides}) bacteria are able to transform AFs into a new undefined product. In the following years, it was shown that other microorganisms also exhibit this feature. These include bacteria such as \textit{F. aurantiacum} [23–26], \textit{Rhodococcus erythropolis}, and \textit{Mycobacterium fluoranthenivorans} [27], \textit{Acinetobacter calcoaceticus} [28], \textit{Bacillus megaterium} [29], \textit{Oenococcus oeni} [30], \textit{Bifidobacterium sp.} [31,32], \textit{Lactobacillus sp.} [31–40], yeasts such as \textit{Saccharomyces cerevisiae}, \textit{Kluyveromyces marxianus}, \textit{Rhodotorula rubra}, \textit{Kloeckera apiculata}, \textit{Candida famata} [41–46], and filamentous fungi from \textit{Aspergillus}, \textit{Penicillium}, \textit{Rhizopus}, and \textit{Aureobasidium} genera [47–51].

Given the limitations of physical and chemical methods of decontamination, biological methods using microorganisms or their enzymes are becoming the focus of more research. Approximately 50% of the publications presented in Figure 3 concerned biological methods of decontamination. Until 2010, most publications focused on the search for microorganisms capable of removing aflatoxin B1 (AFB1), and to a lesser extent other mycotoxins (OTA, patulin, and \textit{Fusarium} mycotoxins). The aim was often to reduce the number of mycotoxins under model conditions, in a buffer or microbiological medium, sometimes related to food or feed [30,33,41,48,49]. Some authors described possible decontamination mechanisms, such as enzymatic biotransformation [26,47,50,51] or adsorption to microbial cells [23,34,36,40,41,44,48].

After 2010, more advanced research attempted to explain the mechanisms of action by microorganisms. Table 1 presents the subjects of reports from the last 10 years, showing the types of microorganisms, the types of mycotoxins, and the proposed decontamination mechanisms.

As can be seen in Table 1, most studies have focused on the use of bacteria for mycotoxin decontamination. In total, 33 species have been studied from \textit{Alcaligenes}, \textit{Bacillus}, \textit{Brevibacterium}, \textit{Cupriavidus}, \textit{Defosia}, \textit{Escherichia}, \textit{Enterobacter}, \textit{Lysinibacter}, \textit{Lysinibacillus}, \textit{Pedococcus}, \textit{Pseudomonas}, \textit{Rhodococcus}, and \textit{Streptomyces}, as well as lactic acid bacteria. Three consortia of bacteria isolated from soil, compost, and kefir grains were also examined. Fewer studies concerned fungi, most of which focused on the use of yeasts for the decontamination of mycotoxins.
Table 1. Reports concerning the microbial decontamination of mycotoxins in the years 2011–2021.

| Microorganisms | Targeted Mycotoxins | Mechanism | References |
|----------------|---------------------|-----------|------------|
| *Alcaligenes faecalis* | OTA | Biotransformation into less toxic products due to laccase activity | [52] |
| *Bacillus amyloliquefaciens* | OTA | Biotransformation into OTα due to carboxypeptidase activity | [53] |
| *Bacillus amyloliquefaciens* | ZEN | Adsorption to bacterial cells | [54] |
| *Bacillus licheniformis* | ZEN | Adsorption to bacterial cells | [55] |
| *Bacillus megaterium* | OTA | Adsorption to bacterial cells | [56] |
| *Bacillus pumilus* | ZEN | Biotransformation due to esterase activity | [57] |
| *Bacillus subtilis* | AFB1 | Biotransformation into less toxic products due to laccase activity | [58] |
| *Bacillus subtilis* | DON | NA | [59] |
| *Bacillus subtilis* | OTA | Adsorption to bacterial cells | [60] |
| *Bacillus subtilis* | ZEN; 17-β-estradiol | Biotransformation into ZEN-14-phosphate and 17-β-estradiol-3-phosphate | [61] |
| *Bacillus velezensis* | OTA | Biodegradation to OTα | [62] |
| *Cupriavidus numazuensis; C. oxalaticus, C. basilensis, C. metallidurans* | OTA, AFB1, ZEN, T-2 | Biotransformation into undefined products with lower toxicity | [64,65] |
| *Devosia insulae* | DON | Biotransformation into 3-keto-DON | [66] |
| *Escherichia coli* | AFB1 | Biotransformation into less toxic products (C_{18}H_{14}O_{7} and other metabolites) | [67] |
| *Enterobacter cloacae subsp. dissolvens* | PAT | Enzymatic biotransformation into E-ascladiol | [68] |
| *Gluconobacter oxydans* | AFB1, OTA, CIT, PAT | Physical binding to bacterial cell wall proteins and polysaccharides | [69] |
| *Lactiplantibacillus plantarum* | OTA | Adsorption into the bacterial cell wall | [70] |
| *Lactiplantibacillus plantarum* | PAT | Biotransformation into E-ascladiol | [71] |
| *Lactobacillus casei* | OTA | Simultaneous partial biotransformation into an undefined product and adsorption into the bacterial cell wall | [72] |
| *Lactiplantibacillus plantarum* | ZEN | NA | [73] |
| *Lactiplantibacillus plantarum* | ZEN | Biotransformation due to esterase activity | [74] |
| *Lysinibacillus sp.* | OTA | Biotransformation into undefined less genotoxic products | [75] |
| *Nocardiales* | OTA | Biodegradation into OTα | [76] |
| *Pediococcus parvulus* | OTA | Biotransformation into 3-keto-DON and 3-epi-DON as intermediate products | [77] |
| *Pseudomonas halotolerans* | DON | Biotransformation into less-toxic 3-keto-DON by oxidation of the C3 hydroxyl group | [78] |
| *Rhodococcus pyridinivorans* | AFB1 | Non-enzymatic transformation into C_{17}H_{14}O_{7} | [79] |
| *Rhodococcus erythropolis, R. rhodochrous, R. pyridinivorans* | AFB1, T-2 | Biotransformation into undefined less genotoxic products | [80] |
| *Rhodococcus jewellery, R. rhodechrous, R. pyridinivorans* | AFB1 | Biodegradation into undefined non-genotoxic products | [81] |
| *Sphingomonadales family* | AFB1 | Biotransformation into undefined hydrolyzed product due to carboxyesterase activity | [82] |
| *Streptomyces spp.* | AFB1 | Biotransformation into undefined less genotoxic products | [83] |
| *Bacterial consortium isolated from soil (Methylophilus; Hyphomicrobium; Ancylobacter; Pseudomonas; Prosthecomicrobium; Tannella; Bosea, and other genera)* | DON | Biotransformation into 3-keto-DON | [84] |
| *Microorganisms from Kefir grains (Lentilactobacillus kefiri 1, Kazachstania servazzii 2 and Acetobacter xyangii)* | AFB1, ZEN, OTA | Adsorption | [85] |
| *Bacterial consortium consists of Geobacillus, Tepidimicrobium, Clostridium and Aeribacillus* | AFB1, ZEN | NA | [86] |
| *Bacterial consortium isolated from spent mushroom compost: Pseudomonas, Camononas, Delfia, Sphingobacterium, Achromobacter* | FB1 | Enzymatic transformation into low-toxicity metabolites | [87] |
### Table 1. Cont.

| Microorganisms | Targeted Mycotoxins | Mechanism | References |
|----------------|---------------------|-----------|------------|
| Candida guilliermondii | PAT | Biotransformation into E-ascladiol with short-chain dehydrogenase/reductase | [90,91] |
| Candida parapsilosis | ZEN | Biotransformation into less toxic β-zearalenol (β-ZOL) and zearalenone-14,16-diglucosid | [92] |
| Candida utilis | ZEN, OTA, AFB1 | Adsorption into cell wall preparation | [93] |
| Kodamaea ohmeri | ZEN, OTA, AFB1 | Adsorption into cell wall preparation | [94] |
| Komagataella phaffi | PAT | Biotransformation into undefined products | [95] |
| Meyerozyma guilliermondii | PAT | Biotransformation into undefined products | [96] |
| Metschnikowia pulcherrima | OTA | Biodegradation | [97] |
| Meyerozyma guilliermondii | OTA | Biotransformation into undefined products | [98,99] |
| Pichia caribbica | PAT | Enzymatic biodegradation | [100] |
| Rhodosporidium kratochvilovae | PAT | Biotransformation into desoxypatulinic acid | [101,102] |
| Rhodotorula mucilaginosa | PAT | Enzymatic biotransformation by orotate phosphoribosyltransferase | [103,104] |
| Saccharomyces cerevisiae | OTA | Adsorption by cell wall polysaccharides | [105,106] |
| Saccharomyces cerevisiae | OTA | Adsorption by yeast cells | [107,108] |
| Saccharomyces cerevisiae, S. pastorianus | OTA | Adsorption by yeast cells | [109] |
| Saccharomyces cerevisiae, S. pastorianus | OTA | Adsorption by yeast cells | [110] |
| Yarrowia lipolytica | OTA | Adsorption | [111] |
| Microorganisms isolated from Kombucha culture: Pichia occidentalis, Candida sorboxylosa and Hanseniaspora opuntiae | AFB1 | Biodegradation into less toxic products | [112] |
| Aspergillus niger | OTA | Biodegradation into ochratoxin α by extracellular ochratoxinase | [113] |
| Aspergillus niger | AFB1 | Biodegradation into AFB2-GOH | [114] |
| Byssochlamys nivea | PAT | Biodegradation | [115] |
| Clonostachys rosea | ZEA | Biotransformation into a less toxic product due to lactonase activity followed by decarboxylation | [116] |
| Rhizopus orzeae, Trichoderma reesei | AFB1 | Biodegradation into less toxic products | [117] |
| Cladosporium sp. | AFB1 | Biodegradation into less cytotoxic products | [118] |

1 formerly belonging to Lactobacillus genera. AFB1—aflatoxin B1; OTA—ochratoxin A; PAT—patulin; ZEN—zearalene; DON—deoxynivalenol; CIT—citrinin; FB1—fumonisin B1; AOH—alternariol; AME—alternariol monomethyl ether; AFB2-GOH—AFB2 coupling with glutathione; 2 yeasts strain; NA—detailed data unavailable.

The studies of microbial activity aimed at the removal of mycotoxins discussed so far have been mainly of a scientific nature, allowing for a better understanding of the strains, their properties, and their mechanisms of action, rather than leading to practical applications. Two main methods of microbial decontamination are identified in the literature: adsorption to the cell wall compounds (peptidoglycan, glucomannan, β-D-glucan) and biotransformation to less toxic or non-toxic compounds, thanks to the expression of appropriate enzymes. Biotransformation takes place along different pathways, by the reduction of ketone carbonyl groups, modification of phenolic hydroxyl groups, the hydrolysis of lactone rings, or the creation of connections with glutathione, deamination, or decarboxylation.

The use of microorganisms or their cell components for the decontamination of foods and feeds could have great potential. However, there are still no legal regulations concerning the decontamination of food detoxification processes that can be applied to products destined for use as animal feed. According to Commission Regulation (EC) 386/2009 in the feed technological additives category, a new functional group was created, composed of “substances for reduction of the contamination of feed by mycotoxins”. These are sub-
stances that can suppress or reduce the absorption of mycotoxins, promote the excretion of mycotoxins, or modify their mode of action, and thereby mitigate possible adverse effects of mycotoxins on animal health [121].

The rules on the detoxification of feed are contained in Commission Regulation (EU) 2015/786. Acceptable detoxification processes should ensure that feed subjected to detoxification processes does not adversely affect the health of either the farm animals or the consumers of food of animal origin (Figure 4). It should also be effective and irreversible, without changing the properties (e.g., nutritional properties) of the feed. The detoxification process should be performed in a facility approved for the purpose by a competent authority. Only detoxification methods that have obtained a positive EFSA scientific opinion and have been approved by competent institutions may be used [122].

Figure 4. Criteria for acceptability of microbiological decontamination methods.

One of the methods of feed detoxification approved by the relevant institutions is the commercial enzyme-based additive FUMzyme®, produced by Biomin GmbH, Austria. This product contains fumonisin esterase, produced by a genetically modified Komagataella pastoris yeasts strain. The additive is already authorized for use with all pigs, all poultry, and all avian species [123]. According to Rychen et al. [95], when added to feed contamination by FB1, fumonisin esterase is able to significantly reduce the concentration of fumonisin B1 in animal feces and at various points in the digestive tract. This is the result of complete or partial fumonisin de-esterification to less toxic products. FUMzyme® does not have any adverse effect on animal health at the recommended maximum dose 300 U/kg of complete feedstuff. Moreover, it is safe for consumers of animal products [123].

As shown in Figure 4, the first criterion of acceptability for a microbiological decontamination method is a well-characterized and accepted microorganism. Microorganisms that can effectively remove mycotoxins (Table 1) include newly isolated species that have so far been poorly characterized. Cupriavidus spp. belonging to the Burkholderiaceae family are relatively poorly understood bacteria, which can be isolated from soil, root nodules, sewage, and aquatic environments [124]. Other examples of newly isolated microorganisms are Pelagibacterium halotolerans, a novel marine halotolerant species of bacteria [125], and Devosia insulae [126]. Only microorganisms that are well known, safe, and characterized in terms of pathogenicity can be used for decontamination. Some of the bacteria and yeasts listed in Table 1 can cause infections in humans. These include Alcaligenes faecalis, which is often associated with local and systemic infections in humans (endocarditis, bacteremia, meningitis, endophthalmitis, skin and soft tissue infections, urinary tract infections, otitis
media, peritonitis, and pneumonia) [127] and Enterobacter cloacae complex strains [128,129], as well as Candida guillermondii and C. parapsilosis, which are in the group of six pathogenic species of yeast responsible for invasive candidiasis [130]. Most infections caused by the bacteria and yeasts listed in Table 1 are opportunistic infections.

Safe and practical methods that could potentially be acceptable to consumers include the use of lactic acid bacteria and selected species of yeasts or microorganism enzymes. These methods can be used during biotechnological processes for the production of fermented food, such as dairy products, vegetable silages, wine, beer, or sourdough. However, the levels of mycotoxin contamination in the raw materials should still not exceed the accepted levels established in EU Regulation 1881/2006 [11].

4.1. Lactic Acid Bacteria

Lactic acid bacteria, including probiotic strains, are of particular interest due to their beneficial physiological effects on human and animal health and their ability bind mutagens from food and the environment [131]. LAB have traditionally been used as natural food and feed preservatives.

Aflatoxin B1, zearalenone, and ochratoxin A have been found to be effectively bound by Lacticaseibacillus rhamnosus probiotic strains [31,38,132]. El-Nezami et al. [34,133] showed that this process can be very fast. After only 4 h of contact between the bacteria and AFB1, the initial amount of AFB1 (5 µg/mL) decreased by between 50% and 77%, depending on the strain, pH, temperature, and biomass density. According to these authors, AFB1 was predominantly bound to the carbohydrate components of cells. Hydrophobic and electrostatic interactions played a major role in this process.

Lactobacillus acidophilus and L. rhamnosus strains are also characterized by the ability to remove AFM1 from milk, with effectiveness ranging from 18% to 57%, depending on the strain [33].

The adsorption of ochratoxin A to the cell wall of Lactiplantibacillus plantarum, Levilactobacillus brevis, and Fructilactobacillus sanfranciscensis has been demonstrated in [70]. Using heat-inactivated lactic acid bacteria biomass, the reduction in the amount of the toxin was several times more efficient than using the same density of viable cell biomass. These findings confirm that toxins are adsorbed into the bacterial cells, especially into the peptidoglycan, as in [34]. The better adsorption of mycotoxins by dead cells compared with live cells may be due to changes in the structures of the bacterial cell walls under the influence of high temperature—i.e., denaturation of proteins, generation of pores in the cell wall structure (which increases the permeability of the outer layers of the cell wall), and increased numbers of active areas responsible for the adsorption of various compounds [33,70].

Niderkorn et al. [134] selected lactic and propionic fermentation bacteria for the removal of Fusarium toxins from solutions. Lacticaseibacillus rhamnosus removed 55% of deoxynivalenol. Leuconostoc mesenteroides removed 82% of fumonisin B1, whereas Lactococcus lactis removed 100% of fumonisin B1. In vivo experiments showed that the use of a symbiotic preparation with selected probiotic strains of the Lactobacillaceae family as feed additives reduced the effects of ochratoxicosis in chickens, as well as having a beneficial influence on the gastrointestinal tract of chickens [135].

Most reports on decontamination by lactic acid bacteria concern aflatoxin B1 and ochratoxin A. The main mechanism responsible for the detoxification of these bacteria is adsorption to the bacterial cell wall. Biotransformations into other products have been reported for patulin and zearalenone (Table 1). Wei et al. [71] tested Lactiplantibacillus plantarum strains isolated from traditional Chinese fermented food for their ability to detoxify patulin. One strain, 13M5, showed the ability to transform patulin into less toxic E-ascaladiol. A similar result was obtained by Zheng et al. [72], who used the Lacticaseibacillus casei YZU01 strain to remove patulin from apple and pear juice. However, in this case, as well as the main mechanism of biotransformation into E-ascaladiol, adsorption of the toxin into the bacterial cells was observed. In a study by Chen et al. [74], Lactiplantibacillus
plantarum strains isolated from faeces and the digestive tracts of leaf-nosed bats and ducks were able to degrade ZEA, due to bacterial esterase activity.

The second condition that a microbiological method must meet is the irreversibility of the process (Figure 4). To avoid desorption and re-exposure to toxins, the mycotoxin-adsorbent complex should be stable, especially under gastrointestinal conditions. However, in some cases the adsorbed mycotoxins are released [40,70]. It has been shown in model studies that toxins bound using thermally inactivated LAB cells are more stable than toxins bound using live bacteria [136].

4.2. Yeasts

Yeasts are the second group of organisms with important potential applications, especially *Saccharomyces cerevisiae* strains. These organisms are widely used in many biotechnological processes, such as baking, brewing, winemaking, and distilling. Several studies have shown that yeasts can effectively remove different mycotoxins from plant-derived raw materials during fermentation, and in model conditions from microbiological media [41–46,106,108–110].

Patulin in apple and fruit-based food and drink poses a risk to consumer health. Therefore, methods are sought to minimize patulin contamination. Zhang et al. [105] studied patulin adsorption by *Saccharomyces cerevisiae* during fermentation in a model medium spiked with PAT. After 48 h of fermentation, almost 90% of the initial content of PAT was removed. The efficiency of adsorption was found to depend on the duration and temperature of fermentation, as well as the initial PAT concentration. The authors concluded that the toxin was absorbed into the cell wall proteins and polysaccharides. In several studies on patulin removal, a different mechanism was demonstrated. Marine yeast identified as *Kodameae ohmeri* was able to transform PAT to E- and Z-ascladiol. The efficiency of the process was highest at pH 3–6, temperature 35 °C, and an inoculum density of around 5 × 10⁸ cells/mL [94]. After incubation of PAT with *Rhodotorula kratochvilvoue*, which is less toxic than PAT, desoxypatulinic acid was formed. The authors suggest that the lower toxicity of desoxypatulinic acid is a consequence of the hydrolysis of the lactone ring and the loss of functional groups that react with thiol groups [101]. In a study by Reddy et al. [97], patulin was effectively degraded by 87.4% after 48 h of fermentation by *Metschnikowia pulcherrima*. Patulin was not detected in the yeast cell walls, which indicates that the yeast did not adsorb PAT but degraded it to an unidentified product of unknown toxicity.

Mycotoxins, especially those produced by *Fusarium* pathogens, pose a problem in breweries. Barley malt can be contaminated with ZEN, DON, and their derivatives FUM and OTA, which can be transferred to malting and brewing by-products [137]. The use of appropriate strains of decontaminable yeast in the production process can improve the quality of the finished products. Nathanail et al. [109] demonstrated that *Saccharomyces pastorianus* lager yeast was able to reduce mycotoxin levels during fermentation of wort naturally contaminated by *Fusarium* trichothecenes. After the 96 h of fermentation, reductions in the numbers of mycotoxins were observed of up to 15% for DON, 17% for DON-3 glucoside, 34% for HT2, and 31% for T2. Since trichothecene metabolites were detected in the beer, the authors suggest that the reactions behind the reduction in mycotoxins may be glucose–sulfate conjugation and deacetylation. Another proposed mechanism was physical binding of the mycotoxins to the yeast cell. Since spent yeast is often used as animal feed, it is important to investigate the stability of the mycotoxin–cell wall complex under gastrointestinal conditions. According to Wall-Martínez et al. [110], the main mechanism of mycotoxin removal during fermentation of contaminated wort is adsorption to the yeast cell wall. After fermentation by the brewer’s yeasts *S. cerevisiae* and *S. pastorianus*, 10–17% of DON and 30–70% of ZEN was removed. The initial concentrations of DON and ZEN in the yeast biomass were 6.4% and 31.3%, respectively. In unfiltered beers, this can be a problem due to the secondary exposure of consumers to mycotoxins, especially as adsorption is reversible at the low pH conditions in the gastrointestinal tract.
Cereals and their derivatives, such as flour and bread, are often contaminated by mycotoxins, mainly OTA and *Fusarium* toxins. The production of sourdough using *Saccharomyces cerevisiae* yeast and lactic acid bacteria reduces the mycotoxin content [38]. Mozaffary et al. [108] found that during dough fermentation *S. cerevisiae* baker’s yeast was able to reduce the amount of OTA in wheat flour by about 60%.

After cereals, the second major source of exposure to OTA is wine. Ochratoxin A contamination is caused by toxigenic fungi such as *Aspergillus carbonarius*, *A. niger*, and *A. awamori*, which grow on grapes [138]. Certain oenological strains of *Saccharomyces* sp. yeasts are able to remove OTA from grape musts during winemaking [41,106,139,140]. Cecchini et al. [140] demonstrated that, depending on the yeast strain, wine yeasts are able to remove 46.8–52.2% of the OTA in white wine and 53.2–70.1% of the OTA in red wine during the fermentation process. The absence of degradation products suggested an adsorption mechanism.

The process of removing OTA from grape juice is very fast. In one study, after just 5 min of contact with yeast cells, 90% of the initial toxin content (10 µg/mL) was adsorbed [41]. Similar results were obtained during fermentation of white grape and blackcurrant musts. Fermentation with *Saccharomyces bayanus* resulted in the removal of more than 60% of OTA from wine [106]. Different results, indicating biotransformation, were obtained by Freire et al. [141] during fermentation of grape must artificially contaminated with toxigenic strains of *A. carbonarius* and *A. niger*. The reductions in OTA concentrations ranged from 88.2% to 92.4%, depending on the type of wine. Metabolites such as ochratoxin B, ochratoxin α methyl ester, ochratoxin B methyl ester, ochratoxin A methyl ester, ethylamide ochratoxin A, ochratoxin C, and ochratoxin A glucose ester were also detected. When red grape must contaminated with OTA was fermented by *Metschnikowia pulcherrima*, products of OTA biodegradation (α-OTA and the sodium adduct of α-OTA without the coumarin group) were identified [99].

Some studies have investigated the possibility of using dead yeast cells from appropriate strains as adsorbents in oenological practice [41,106]. Such adsorbents are inexpensive, safe, and do not affect the organoleptic properties of the wine. However, the disposal of the residue is controversial since the toxin can desorb from the yeast cell–OTA complex. Another disadvantage of this method of decontamination is that it binds other ingredients that contribute to wine quality, such as polyphenols and anthocyanins [142]. Petruzzi et al. [143] demonstrated that the process of OTA binding by *Saccharomyces cerevisiae* is reversible and that the stability of the OTA–yeast cell complex depends on the kind of strain, the pH, and the sugar concentration.

5. Mycotoxin Adsorbents of Microbial Origin

Another approach to mycotoxin decontamination is the addition of inert dietary supplements to feed, such as clays, kaolin, zeolites, activated carbon, sodium, and magnesium aluminum silicates, as well as hydrated sodium calcium aluminum silicate (HSCAS) or bentonite [144]. These supplements effectively adsorb toxins in the feed or in the digestive tract of animals. As a result, the toxins are not absorbed into the bloodstream and their resorption is prevented. Various inorganic adsorbents are commercially available and some of them are enriched with enzymes. However, the major disadvantage of adsorbents is that they can also bind vitamins, micro- and macro-elements, as well as other essential compounds, thereby reducing the nutritional value of the feed.

The dominant mechanism responsible for the removal of mycotoxins using microorganisms is adsorption to bacterial and yeast cells. Given the many limitations regarding the use of live microorganisms to remove mycotoxins, the use of microbial adsorbents for this purpose offers a promising solution. Most research has focused on preparations containing β-D-glucans extracted from *S. cerevisiae* yeast cell walls. Yeasts cell wall components have been used to adsorb a variety of toxins, including *Fusarium* and *Alternaria* toxins, as well as OTA and AFB1 [42,93,107,111,145,146]. In a study by Bzducha et al. [93], the cell walls and
β-glucans isolated from *Candida utilis* were characterized by the greatest ability to bind non-polar mycotoxins, such as ZEN, OTA, and AFB1, especially under acidic conditions. Freimund et al. [42] showed that crosslinked 1,3-β-D-glucan modified by carboxymethyl ether and hexadecyltrimethylammonium salt was able to efficiently adsorb zearalenone and T-2 toxin.

Research on OTA adsorption under model conditions has shown that the polysaccharide fraction of the brewery yeast cell, water-extracted glucan, and commercial glucan adsorbed the highest amounts of OTA, at more than 55% of the initial concentration. Adsorption is most effective at a close-to-neutral pH and is considerably less effective under alkaline conditions. The polysaccharide fraction of the yeast cell wall, namely β-glucans, is responsible for the adsorption of ochratoxin A [107]. Yiannikouris et al. [147] found that zearalenone adsorption provided by β-(1,3)-D-glucans is most effective under acidic and neutral conditions. These conditions are present in some parts of the digestive tract of animals, which suggests that β-(1,3)-D-glucans may be effective as feed additives. Different results were obtained in a study on the adsorption of *Alternaria* toxins (AOH and AME) by thermally deactivated yeasts. In an alkaline environment at pH 9, the toxins were almost completely removed by the yeast powder at a concentration of 40 g/L [111].

Yeasts and their cell wall components are used both as feed additives for animals and as adsorbents that effectively limit mycotoxicosis in farm animals. Raju and Devegowda [148] suggest that the esterified form of β-D-glucan from yeast cell walls can help to protect broiler chickens exposed to aflatoxin B1, ochratoxin A, and T-2 toxin, individually and in combination. The potential application of glucans and yeast cell wall derivatives as mycotoxin adsorbents in feed depends on the stability of the toxin–cell wall complex under the conditions of the gastrointestinal tract. Analysis of the adsorption of OTA by yeast cell wall extract during simulated consecutive digestion steps revealed that more than 80% of the OTA was bound at pH 2.5. The resulting complex was stable after the action of digestive enzymes (pepsin, pancreatin). However, some of the OTA was released when the pH was raised to 6.5.

An in vivo study on broiler chickens showed that OTA deposits in the livers of chickens given contaminated feed containing cell wall extract were 30% lower after 14 days than the levels of OTA in the control group given contaminated feed without the extract [149]. This result was supported by Ejiofor et al. [150], who found that the addition of 2 g of *S. cerevisiae* yeast to 1 kg of feed neutralized the negative impact of feed naturally contaminated with AFs and DON on the histopathological, hematological, and serum biochemical parameters of chickens, although to a lesser extent than kaolin adsorbent.

Overall, the research literature suggests that adsorbents can be used as functional feed additives, increasing the efficiency and health of poultry exposed to mycotoxins in feed. These findings may be of interest and use to feed producers and livestock breeders.

6. Conclusions

This review has surveyed the literature regarding the removal of mycotoxins from food and feed, with a special focus on microbiological methods. Although the decontamination of food using microorganisms has many advantages, there are still no legal regulations concerning the decontamination of food (Figure 5). Biological detoxification processes can, however, be applied to products used as animal feed.

Methods that could be used safely and be acceptable to consumers include the use of lactic acid bacteria and selected yeast species, which can be used in the production of fermented foods such as dairy products, vegetable silages, wine, beer, and sourdough. Selected strains with appropriate technological features could also reduce the content of toxins, increasing the safety of the final product. Another possibility is the addition of dietary supplements to feed, which can effectively adsorb toxins directly in the feed or in the digestive tract of animals. As a result, the toxins are not absorbed into the bloodstream. Yeasts and their cell wall derivatives can be used to adsorb a variety of toxins, including *Fusarium* and *Alternaria* toxins, as well as OTA and AFB1. More research is needed to
ensure that these methods meet the many standards required for practical usage. The environmental risk of residues containing toxins, as well as economic aspects, should also be considered.

Figure 5. Advantages and limitations of biological methods of decontamination.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The author declares no conflict of interest.

**References**

1. Murphy, P.A.; Hendrich, S.; Landgren, C.; Bryant, C.M. Food mycotoxins: An update. *J. Food Sci.* 2006, 71, R51–R65. [CrossRef]
2. Richard, J.L. Some major mycotoxins and their mycotoxicoses—An overview. *Int. J. Food Microbiol.* 2007, 119, 3–10. [CrossRef] [PubMed]
3. Alassane-Kpembi, I.; Schatzmayr, G.; Taranu, I.; Marin, D.; Puel, O.; Oswald, I.P. Mycotoxins co-contamination: Methodological aspects and biological relevance of combined toxicity studies. *Crit. Rev. Food Sci. Nutr.* 2017, 57, 3489–3507. [CrossRef]
4. European Commission. Commission Regulation (EU) 2019/1901 of 7 November 2019 amending Regulation (EC) No 1881/2006 as regards maximum levels of citrinin in food supplements based on rice fermented with red yeast Monascus purpureus. *Off. J. Eur. Union* 2019, 62, 2–4.
5. European Commission. Commission Regulation (EU) 2015/1137 of 13 July 2015 amending Regulation (EC) No 1881/2006 as regards the maximum level of Ochratoxin A in Capsicum spp. spices. *Off. J. Eur. Union* 2015, 58, 11–12.
6. European Commission. Commission Regulation (EU) No 1058/2012 of 12 November 2012 amending Regulation (EC) No 1881/2006 as regards maximum levels for aflatoxins in dried figs. *Off. J. Eur. Union* 2012, 55, 14–15.
7. European Commission. Commission Regulation (EU) No 594/2012 of 5 July 2012 amending Regulation (EC) 1881/2006 as regards the maximum levels of the contaminants ochratoxin A, non dioxin-like PCBs and melamine in foodstuffs. *Off. J. Eur. Union* 2012, 55, 43–45.
8. European Commission. Commission Regulation (EU) No 165/2010 of 26 February 2010 amending Regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs as regards aflatoxins. *Off. J. Eur. Union* 2010, 50, 8–12.
9. European Commission. Commission Regulation (EU) No 105/2010 of 5 February 2010 amending Regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs as regards ochratoxin A. *Off. J. Eur. Union* 2010, 53, 7–8.
10. European Commission. Commission Regulation (EC) No 1126/2007 of 28 September 2007 amending Regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs as regards *Fusarium* toxins in maize and maize products. *Off. J. Eur. Union* 2007, 50, 14–18.
11. European Commission. Commission Regulation (EC) No 1881/2006 of 19 December 2006. Setting maximum levels for certain contaminants in foodstuffs. *Off. J. Eur. Union* 2006, 364, 324–365.
12. European Commission. Commission Recommendation of 17 August 2006 on the presence of deoxynivalenol, zearalenone, ochratoxin A, T-2 and HT-2 and fumonisins in products intended for animal feeding. Off. J. Eur. Union 2006, 49, 7–9.

13. Boutrif, E.; Canet, C. Mycotoxin prevention and control: FAO programmes. Rev. Med. Vet. 1998, 149, 681–694.

14. Eskola, M.; Kos, G.; Elliott, C.T.; Hajslova, J.; Mayar, S.; Krksa, R. Worldwide contamination of food-crops with mycotoxins: Validity of the widely cited ‘FAO estimate’ of 25%. Crit. Rev. Food Sci. Nutr. 2020, 60, 2773–2789. [CrossRef]

15. Lee, H.J.; Ryu, D. Worldwide occurrence of mycotoxins in cereals and cereal-derived food products: Public Health Perspectives of Their Co-occurrence. J. Agric. Food Chem. 2017, 65, 7034–7051. [CrossRef] [PubMed]

16. Biomin. Mycotoxin Survey. Occurrence and Risk Level Indicator. Available online: https://www.biomin.net/solutions/mycotoxin-survey (accessed on 12 October 2021).

17. Zhang, Z.; Nie, D.; Fan, K.; Yang, J.; Guo, W.; Meng, J.; Zhao, Z.; Han, Z. A systematic review of plant-conjugated masked mycotoxins: Occurrence, toxicity, and metabolism. Crit. Rev. Food Sci. Nutr. 2019, 60, 1523–1537. [CrossRef] [PubMed]

18. European Commission. Commission Recommendation of 17 August 2006 on the prevention and reduction of Fusarium toxins in cereals and cereal products. Off. J. Eur. Union 2006, 49, 35–40.

19. Nunes, V.M.; Moosavi, M.; Khaneghah, A.M.; Oliveira, C.A. Innovative modifications in food processing to reduce the levels of mycotoxins. Curr. Opin. Food Sci. 2021, 38, 155–161. [CrossRef]

20. Marshall, H.; Meneely, J.P.; Quinn, B.; Zhao, Y.; Bourke, P.; Gilmore, B.F.; Zhang, G.; Elliott, C.T. Novel decontamination approaches and their potential application for post-harvest aflatoxin control. Trends Food Sci. Technol. 2020, 106, 489–496. [CrossRef]

21. Conte, G.; Fontanelli, M.; Galli, F.; CotroZZi, L.; Pagni, L.; Pellegrini, E. Mycotoxins in feed and food and the role of ozone in their detoxification and degradation: An Update. Toxins 2020, 12, 486. [CrossRef] [PubMed]

22. Ciegler, A.; Lillehoj, E.B.; Peterson, R.E.; Hall, H.H. Microbial detoxification of aflatoxin. Appl. Microbiol. 1966, 14, 934–939. [CrossRef]

23. Dsouza, D.; Brackett, R.E. Aflatoxin B1 degradation by Flavobacterium aurantiacum in the presence of reducing conditions and seryl and sulphydryl group inhibitors. J. Food Prot. 2001, 64, 268–271. [CrossRef] [PubMed]

24. Hao, Y.-Y.; Brackett, R.E. Removal of aflatoxin B1 from peanut milk inoculated with Flavobacterium aurantiacum. J. Food Sci. 1988, 53, 1384–1386. [CrossRef]

25. Line, J.E.; Brackett, R.E. Factors aAfecting aflatoxin B1 removal by Flavobacterium aurantiacum. J. Food Prot. 1995, 58, 91–94. [CrossRef] [PubMed]

26. Smiley, R.D.; Draughon, F.A. Preliminary evidence that degradation of aflatoxin B1 by Flavobacterium aurantiacum is enzymatic. J. Food Prot. 2000, 63, 415–418. [CrossRef]

27. Teniola, O.; Addo, P.; Brost, I.; Farber, P.; Jany, K.; Alberts, J.; Vanzyl, W.; Steyn, P.; Holzapfel, W. Degradation of aflatoxin B1 by cell-free extracts of Rhodococcus erythropolis and Mycobacterium fluoranthenivorans sp. nov. DSM44556T. Int. J. Food Microbiol. 2005, 105, 111–117. [CrossRef]

28. Hwang, C.-A.; DraughonN, F.A. Degradation of ochratoxin A by Acinetobacter calcoaceticus. J. Food Prot. 1994, 57, 410–414. [CrossRef]

29. Engler, K.H.; Coker, R.D.; Evans, I.H. Uptake of aflatoxin B 1 and T-2 toxin by two mycotoxin bioassay microorganisms: Kluvyromycetes marxianus and Bacillus megaterium. Arch. Microbiol. 2000, 174, 381–385. [CrossRef]

30. Mateo, E.M.; Medina, A.; Mateo, F.; Valle-Algarra, F.M.; Pardo, I.; Jiménez, M. Ochratoxin A removal in synthetic media by living and heat-inactivated cells of Oenococcus oeni isolated from wines. Food Control. 2010, 21, 23–28. [CrossRef]

31. Peltonen, K.D.; El-Nezami, H.S.; Salminen, S.J.; Ahokas, J.T. Binding of aflatoxin B1 by probiotic bacteria. J. Sci. Food Agric. 2000, 80, 1942–1945. [CrossRef]

32. Fuchs, S.; Sontag, G.; Stidl, R.; Ehrlich, V.; Kundi, M.; Knasmüller, S. Detoxification of patulin and ochratoxin A, two abundant mycotoxins, by lactic acid bacteria. Food Chem. Microbiol. 2008, 46, 1398–1407. [CrossRef] [PubMed]

33. Pierides, M.; El-Nezami, H.; Peltonen, K.; Salminen, S.; Ahokas, J. Ability of dairy strains of lactic acid bacteria to bind aflatoxin M1 in a food model. J. Food Prot. 2000, 63, 645–650. [CrossRef] [PubMed]

34. El-Nezami, H.; Kankaanpaa, P.; Salminen, S.; Ahokas, J. Ability of dairy strains of lactic acid bacteria to bind a common food carcinogen, aflatoxin B1. Food Chem. Toxicol. 1998, 36, 321–326. [CrossRef]

35. El-Nezami, H.; Mykkänen, H.; Kankaanpää, P.; Salminen, S.; Ahokas, J. Ability of Lactobacillus and Propionibacterium strains to remove aflatoxin B1 from the chicken duodenum. J. Food Prot. 2000, 63, 549–552. [CrossRef]

36. Turbic, A.; Ahokas, J.T.; Haskard, C.A. Selective in vitro binding of dietary mutagens, individually or in combination, by lactic acid bacteria. Food Addit. Contam. 2002, 19, 144–152. [CrossRef]

37. Škrinjar, M.; Rašič, J.; Stojičić, V. Lowering of ochratoxin A level in milk by yoghurt bacteria and bifidobacteria. Folia Microbiol. 1996, 41, 26–28. [CrossRef] [PubMed]

38. Piotrowska, M.; Zakowska, Z. The biodegradation of ochratoxin A in food products by lactic acid bacteria and baker’s yeast. Prog. Biotechnol. 2000, 17, 307–310. [CrossRef]

39. Niderkorn, V.; Boudra, H.; Morgavi, D. Binding of Fusarium mycotoxins by fermentative bacteria in vitro. J. Appl. Microbiol. 2006, 101, 849–856. [CrossRef] [PubMed]

40. Haskard, C.A.; El-Nezami, H.S.; Kankaanpaa, P.E.; Salminen, S.; Ahokas, J. Surface binding of aflatoxin B1 by lactic acid bacteria. Appl. Environ. Microbiol. 2001, 67, 3086–3091. [CrossRef] [PubMed]
41. Bejaoui, H.; Mathieu, F.; Taillandier, P.; Lebrhi, A. Ochratoxin A removal in synthetic and natural grape juices by selected oenological Saccharomyces strains. J. Appl. Microbiol. 2004, 97, 1038–1044. [CrossRef] [PubMed]

42. Freimund, S.; Sauter, M.; Rys, P. Efficient adsorption of the mycotoxins zearalenone and T-2 toxin on a modified yeast glucan. J. Environ. Sci. Health Part B 2003, 38, 243–255. [CrossRef] [PubMed]

43. Shetty, P.H.; Hald, B.; Jespersen, L. Surface binding of aflatoxin B1 by Saccharomyces cerevisiae strains with potential decontaminating abilities in indigenous fermented foods. Int. J. Food Microbiol. 2007, 113, 41–46. [CrossRef] [PubMed]

44. Angioni, A.; Caboni, P.; Garau, A.; Farris, A.; Orro, D.; Budroni, M.; Cabras, P. In vitro interaction between ochratoxin A and different strains of Saccharomyces cerevisiae and Kloeckera apiculata. J. Agric. Food Chem. 2007, 55, 2043–2048. [CrossRef] [PubMed]

45. Štyriak, I.; Conková, E.; Kmek, V.; Böhm, J.; Razzazi, E. The use of yeast for microbial degradation of some selected mycotoxins. Mycotoxin Res. 2001, 17, 24–27. [CrossRef] [PubMed]

46. Var, I.; Erginkaya, Z.; Kabak, B. Reduction of ochratoxin A levels in white wine by yeast treatments. J. Inst. Brew. 2009, 115, 30–34. [CrossRef]

47. Abrunhosa, L.; Santos, L.; Venâncio, A. Degradation of ochratoxin A by proteases and by a crude enzyme of Aspergillus niger. Food Biotechnol. 2006, 20, 231–242.

48. Bejaoui, H.; Mathieu, F.; Taillandier, P.; Lebrhi, A. Conidia of black Aspergilli as new biological adsorbents for ochratoxin A in grape juices and musts. J. Agric. Food Chem. 2005, 53, 8224–8229. [CrossRef]

49. Brown, R.L.; Cotty, P.J.; Cleveland, T.E. Efficient adsorption of the mycotoxins zearalenone and T-2 toxin on a modified yeast glucan. J. Agric. Food Chem. 2005, 53, 8224–8229. [CrossRef] [PubMed]

50. Varga, J.; Péteri, Z.; Tábori, K.; Téren, J.; Vágvölgyi, C. Degradation of ochratoxin A and other mycotoxins by Rhizopus isolates. Int. J. Food Microbiol. 2005, 99, 321–328. [CrossRef]

51. Varga, J.; Rigó, K.; Téren, J. Degradation of ochratoxin A by Aspergillus species. Int. J. Food Microbiol. 2000, 59, 1–7. [CrossRef]

52. Zhang, H.H.; Wang, Y.; Zhao, C.; Wang, J.; Zhang, X.L. Biodegradation of ochratoxin A by Alcaligenes faecalis isolated from soil. J. Appl. Microbiol. 2017, 123, 661–668. [CrossRef] [PubMed]

53. Chang, X.; Wu, Z.; Wu, S.; Dai, Y.; Sun, C. Degradation of ochratoxin A by Bacillus amyloliquefaciens ASAG1. Food Addit. Contam. Part A 2015, 32, 564–571. [CrossRef] [PubMed]

54. Lee, A.; Cheng, K.-C.; Liu, J.-R. Isolation and characterization of a Bacillus amyloliquefaciens strain with zearalenone removal ability and its probiotic potential. J. Agric. Food Chem. 2014, 62, e0182220. [CrossRef]

55. Hsu, T.-C.; Yi, P.-J.; Lee, T.-Y.; Liu, J.-R. Isolation and characterization of a Bacillus subtilis strain with zearalenone-removal ability and antifungal activity. Food Control. 2019, 106, 106743. [CrossRef] [PubMed]

56. Wang, G.; Wu, J.; Dong, F.; Shi, J.; Xu, J. Esterase activity inspired selection and characterization of zearalenone degrading bacteria Bacillus pumilus ES-21. Food Control. 2017, 77, 57–64. [CrossRef] [PubMed]

57. Watanaikij, N.; Visesangawan, W.; Petchkongkaew, A. Aflatoxin B1-degrading activity from Bacillus subtilis BCC 42005 isolated from fermented cereal products. Food Addit. Contam. Part A 2020, 37, 1579–1589. [CrossRef] [PubMed]

58. Jia, R.; Cao, L.; Liu, W.; Shen, Z. Detoxification of deoxynivalenol by Bacillus subtilis ASAG 216 and characterization the degradation process. Eur. Food Res. Technol. 2020, 247, 67–76. [CrossRef] [PubMed]

59. Shi, L.; Liang, Z.; Li, J.; Hao, J.; Xu, Y.; Huang, K.; Tian, J.; He, X.; Xu, W. Ochratoxin A biocontrol and biodegradation by Bacillus subtilis CW 14. J. Sci. Food Agric. 2014, 94, 1879–1885. [CrossRef]

60. Bin Yang, S.; Zheng, H.C.; Xu, J.Y.; Zhao, X.Y.; Shu, W.J.; Li, X.M.; Song, H.; Ma, Y.H. New biotransformation mode of zearalenone identified in Bacillus subtilis Y816 revealing a novel ZEN conjugate. J. Agric. Food Chem. 2021, 69, 7409–7419. [CrossRef] [PubMed]

61. Shu, X.; Wang, Y.; Zhou, Q.; Li, M.; Hu, H.; Ma, Y.; Chen, X.; Ni, J.; Zhao, W.; Huang, S.; et al. Biological degradation of aflatoxin B1 by cell-free extracts of Bacillus velezensis DY3108 with broad pH stability and excellent thermostability. Toxins 2018, 10, 330. [CrossRef]

62. Rodríguez, H.; Reveron, I.; Doria, F.; Costantini, A.; Rivas, B.D.L.; Muñoz, R.; García-Moruno, E. Degradation of ochratoxin A by Brevibacterium species. J. Agric. Food Chem. 2011, 59, 10755–10760. [CrossRef]

63. Al-Nussairawi, M.; Risa, A.; Garai, E.; Varga, E.; Szabó, I.; Csenki-Bakos, Z.; Krizs, B.; Cserháti, M. Mycotoxin biodegradation ability of the Cuspariaeus genus. Curr. Microbiol. 2020, 80, 20230–20240. [CrossRef] [PubMed]

64. Ferenczi, S.; Cserháti, M.; Krifaton, C.; Szoboszlai, S.; Kukolya, J.; Szőke, Z.; Köszegi, B.; Albert, M.; Barna, T.; Mézes, M.; et al. A new ochratoxin A biodegradation strategy using Cuspariaeus basileiensis Ōr16 Strain. PLoS ONE 2014, 9, e109817. [CrossRef] [PubMed]

65. Wang, G.; Wang, Y.; Ji, F.; Xu, L.; Yu, M.; Shi, J.; Xu, J. Biodegradation of deoxynivalenol and its derivatives by Devosia insulare A16. Food Chem. 2019, 276, 436–442. [CrossRef] [PubMed]

66. Wang, L.; Wu, J.; Liu, Z.; Shi, Y.; Liu, J.; Xu, X.; Hao, S.; Mu, P.; Deng, F.; Deng, Y. Aflatoxin B1 Degradation and detoxification by Escherichia coli CG1061 isolated from chicken cecum. Front. Pharmacol. 2019, 9, 9. [CrossRef]

67. Xing, M.; Li, B.; Chen, Y.; Tian, S. Ribonucleoside diphosphate reductase plays an important role in patulin degradation by Enterobacter cloacae subsp. dissolvens. J. Agric. Food Chem. 2020, 68, 5232–5240. [CrossRef] [PubMed]

68. Markov, K.; Ferec, J.; Pleadin, J.; Bevardi, M.; Barišić, L.; Klijusurić, J.G.; Vulić, A.; Jakopović, Ž.; Mrvčić, J. Gluconobacter oxydans—Potential biological agent for binding or biotransformation of mycotoxins. World Mycotoxin J. 2019, 12, 153–161. [CrossRef]
70. Piotrowska, M. The Adsorption of ochratoxin A by Lactobacillus species. Toxins 2014, 6, 2826–2839. [CrossRef] [PubMed]

71. Wei, W.; Qian, Y.; Wu, Y.; Chen, Y.; Peng, C.; Luo, M.; Xu, J.; Zhou, Y. Y. Oxidation of ochratoxin A by Lactobacillus species. Toxins 2021, 13, 571–578. [CrossRef] [PubMed]

72. Zheng, H.; Zhang, H.; Qiu, X.; Wang, X.; Wang, Y.; Bin, Y.; Xie, X.; Zheng, F.; Luo, H. Biodegradation of deoxynivalenol by a novel strain of Lactobacillus. Front. Microbiol. 2021, 12, 12. [CrossRef] [PubMed]

73. Abruñolosa, L.; Inés, A.; Rodrigues, A.; Guimarães, A.; Pereira, V.; Parpott, P.; Mendes-Faia, A.; Venâncio, A. Biodegradation of ochratoxin A by Pediococcus parvis late isolated from aurowines. Int. J. Food Microbiol. 2014, 188, 45–52. [CrossRef]

74. Zhang, J.; Qin, X.; Guo, Y.; Zhang, Q.; Ma, Q.; Ji, C.; Zhao, L. Enzymatic degradation of deoxynivalenol by a novel bacterium, Penicillium halotolerans ANSP101. Food Chem. Toxicol. 2020, 140, 111276. [CrossRef]

75. Yao, Y.; Shu, X.; Wang, D.; Kan, W.; Su, P.; Hu, H.; Chen, X.; Wang, D.; Huang, S.; Wu, L. Non-enzymatic transformation of aflatoxin B1 by Pseudomonas aeruginosa m29. Front. Microbiol. 2021, 12, 12. [CrossRef]

76. Wei, C.; Yu, L.; Xiong, Y.; Lin, Y.; Liu, H.; Li, X.; Zhang, C.; Luo, X.; et al. Biological detoxification of fumonisin by a novel fungal consortium. Front. Microbiol. 2021, 12, 12. [CrossRef] [PubMed]

77. Souno, K.; Souno, Y.; Souno, M.; Souno, W.; Souno, T. The mechanism of bioaccumulation and biodegradation of fumonisin B1 and zearalenone by a microbial consortium. Toxicon 2018, 146, 69–76. [CrossRef] [PubMed]

78. Zhao, Z.; Zhang, H.; Gong, A.; Liu, N.; Chen, S.; Zhao, X.; Li, X.; Chen, L.; Zhou, C.; Wang, J. Biodegradation of mycotoxin fumonisin B1 by a novel bacterial consortium. Appl. Microbiol. Biotechnol. 2019, 103, 7129–7140. [CrossRef]

79. Chen, Y.; Peng, H.-M.; Wang, X.; Li, B.-Q.; Ma, N.; Xu, Y.; Meng, X. Patulin biodegradation by marine yeast Kozameae ohmeri. Food Addit. Contam. Part A 2015, 32, 1–9. [CrossRef]

80. Rychen, G.; Aquilina, G.; Azimonti, G.; Bampidis, V.; Bastos, M.D.L.; Bories, G.; Chesson, A.; Cocconcelli, P.S.; Flachowsky, G.; Gropp, J.; et al. Safety and efficacy of fumonisin esterase (FUMzyme®) as a technological feed additive for all avian species. EFSJ 2016, 14, 14. [CrossRef]

81. Fu, Y.; Yang, Q.; Solairaj, D.; Godana, E.A.; Routledge, M.N.; Zhang, H. Biodegradation of mycotoxin patulin by the yeast Meyerozyma guilliermondii. Biol. Control. 2021, 160, 104692. [CrossRef]
97. Reddy, K.R.N.; Spadaro, D.; Gullino, M.L.; Garibaldi, A. Potential of two Metschnikowia pulcherrima (yeast) strains for in vitro biodegradation of patulin. *J. Food Prot.* 2011, 74, 154–156. [CrossRef] [PubMed]

98. Patharajan, S.; Reddy, K.; Karthikeyan, V.; Spadaro, D.; Lore, A.; Gullino, M.; Garibaldi, A. Potential of yeast antagonists on in vitro biodegradation of ochratoxin A. *Food Control.* 2011, 22, 290–296. [CrossRef]

99. Minguez, C.L.; Garrigues, M.A.R.; Ocaña, L.L.; Novella, R.A.; Vinuesa, J.M.; Meca, G. Transformation of ochratoxin A by microorganisms isolated from Tempranillo grapes in wine systems. *Am. J. Enol. Vitic.* 2020, 71, 167–174. [CrossRef]

100. Zheng, X.; Yang, Q.; Zhang, H.; Cao, J.; Zhang, X.; Apaliya, M.T. The possible mechanisms involved in degradation of patulin by *Pichia caribbica*. *Toxins* 2016, 8, 289. [CrossRef]

101. Castoria, R.; Mannina, L.; Durán-Patrón, R.; Maffei, F.; Sobolev, A.P.; De Felice, D.V.; Pinedo-Rivilla, C.; Ritiieni, A.; Ferracane, R.; Wright, S.A.I. Conversion of the mycotoxin patulin to the less toxic deoxypatulinic acid by the biocontrol yeast *Rhodosporidium kratochvilovae* strain LS11. *J. Agric. Food Chem.* 2011, 59, 11571–11578. [CrossRef]

102. Pinedo, C.; Wright, S.A.I.; Collado, I.G.; Goss, R.J.M.; Castoria, R.; Hrelia, P.; Maffei, F.; Durán-Patrón, R. Isotopic labeling studies reveal the patulin detoxification pathway by the biocontrol yeast *Rhodosporidium kratochvilovae* strain LS11. *J. Nat. Prod.* 2018, 81, 2692–2699. [CrossRef]

103. Li, X.; Tang, H.; Yang, C.; Meng, X.; Liu, B. Detoxification of mycotoxin patulin by the yeast *Rhodotorula mucilaginosa*. *Food Control.* 2019, 96, 47–52. [CrossRef]

104. Zhang, Z.; Li, M.; Wu, C.; Peng, B. Physical adsorption of patulin by *Saccharomyces cerevisiae* during fermentation. *J. Food Sci. Technol.* 2019, 56, 2326–2331. [CrossRef]

105. Zhang, Z.; Li, M.; Wu, C.; Peng, B. Physical adsorption of patulin by *Saccharomyces cerevisiae* during fermentation. *J. Food Sci. Technol.* 2019, 56, 2326–2331. [CrossRef]

106. Piotrowska, M.; Nowak, A.; Czyzowska, A. Removal of ochratoxin A by wine *Saccharomyces cerevisiae* strains. *Eur. Food Res. Technol.* 2013, 236, 441–447. [CrossRef]

107. Piotrowska, M.; Masek, A. *Saccharomyces cerevisiae* cell wall components as tools for ochratoxin A decontamination. *Toxins* 2015, 7, 1151–1162. [CrossRef] [PubMed]

108. Mozaffary, P.; Milani, J.M.; Heshmati, A. The influence of yeast level and fermentation temperature on ochratoxin A decrement during bread making. *Food Sci. Nutr.* 2017, 7, 2144–2150. [CrossRef] [PubMed]

109. Nathanael, A.V.; Gibson, B.; Han, L.; Peltonen, K.; Ollilainen, V.; Jestoi, M.; Laitila, A. The lager yeast *Saccharomyces pastorianus* removes and transforms *Fusarium* trichothecene mycotoxins during fermentation of brewer’s wort. *Food Chem.* 2016, 203, 448–455. [CrossRef]

110. Wall-Martínez, H.A.; Pascuri, X.; Bigorda, A.; Ramos, A.J.; Marín, S.; Sanchis, V. The fate of *Fusarium* mycotoxins (deoxynivalenol and zearalenone) through wort fermenting by *Saccharomyces yeasts* (*S. cerevisiae* and *S. pastorianus*). *Food Res. Int.* 2019, 126, 108587. [CrossRef] [PubMed]

111. Wang, X.; Han, Y.; Zhang, L.; Ge, Z.; Liu, M.; Zhao, G.; Zong, W. Removal of *Alternaria* mycotoxins from aqueous solution by inactivated yeast powder. *J. Sci. Food Agric.* 2020, 100, 5182–5190. [CrossRef]

112. Yang, Q.; Wang, J.; Zhang, H.; Li, C.; Zhang, X. Ochratoxin A is degraded by *Yarrowia lipolytica* and generates non-toxic degradation products. *World Mycotox J.* 2016, 9, 269–278. [CrossRef]

113. Ben Taheur, F.; Mansour, C.; Ben Jeddou, K.; Machreï, K.; Khouidi, B.; Abdulhakim, J.A.; Chaieb, K. Aflatoxin B1 degradation by microorganisms isolated from Kombucha culture. *Toxicon* 2020, 179, 76–83. [CrossRef] [PubMed]

114. Zhao, M.; Wang, X.; Xu, S.; Yuan, G.; Shi, X.; Liang, Z. Degradation of ochratoxin A by yeast supernatant and ochratoxinase of *Aspergillus niger* W-35 isolated from cereals. *World Mycotox J.* 2020, 13, 287–298. [CrossRef]

115. Qiu, T.; Wang, H.; Yang, Y.; Yu, J.; Ji, J.; Sun, J.; Zhang, S.; Sun, X. Exploration of biodegradation mechanism by AFB1-degrading strain *Aspergillus niger* FS10 and its metabolic feedback. *Food Control.* 2021, 121, 107609. [CrossRef]

116. Zhang, X.; Guo, Y.; Ma, Y.; Chai, Y.; Li, Y. Biodegradation of patulin by a *Byssoschlamys nivea* strain. *Food Control.* 2016, 64, 142–150. [CrossRef]

117. Zhao, G.; Yang, X.; Nisar, T.; Tian, Y.; Sun, L.; Zhang, X.; Guo, Y. Patulin biodegradation and quality improvement of apple puree fermented with *Byssoschlamys nivea* FFL-2. *Food Biosci.* 2018, 21, 45–52. [CrossRef]

118. Utermöhr, J.; Karlovsky, P. Role of zearalenone lactonase in protection of *Glisecladium roseum* from fungitoxic effects of the mycotoxin zearalenone. *Appl. Environ. Microbiol.* 2007, 73, 637–642. [CrossRef] [PubMed]

119. Hackbart, H.C.S.; Machado, A.R.; Christ-Ribeiro, A.; Prietto, L.; Badiale-Furlong, E. Reduction of aflatoxins by *Rhizopus oryzae* and *Trichoderma reesi*. *Mycoptis Res.* 2014, 30, 141–149. [CrossRef]

120. Ernou, T.; Xin, D.; Wenhao, C.; Changgao, W.; Jianguo, L.; Cai, J. Structure and toxicity analysis of aflatoxin B1 biodegraded products by culture supernatant of *Cladosporium sphericum*. *ScienceAsia* 2020, 46, 308. [CrossRef]

121. European Commission. Commission Regulation (EC) No 386/2009 of 12 May 2009 amending Regulation (EC) No 1831/2003 of the European Parliament and of the Council as regards the establishment of a new functional group of feed additives. *Off. J. Eur. Union* 2009, 52, 66–67.

122. European Commission. Commission Regulation (EU) 2015/786 of 19 May 2015 defining acceptability criteria for detoxification processes applied to products intended for animal feed as provided for in Directive 2002/32/EC of the European Parliament and of the Council. *Off. J. Eur. Union* 2015, 58, 10–14.
149. Vartiainen, S.; Yiannikouris, A.; Apajalahti, J.; A Moran, A.C. Comprehensive evaluation of the efficiency of yeast cell wall extract to adsorb ochratoxin A and mitigate accumulation of the toxin in broiler chickens. *Toxins* 2020, 12, 37. [CrossRef]

150. Ejiofor, T.; Mgbeahuruie, A.C.; Ojiako, C.; Ushie, A.M.; Nwoko, E.I.; Onoja, I.R.; Dada, T.; Mwanza, M.; Karlsson, M. *Saccharomyces cerevisiae*, bentonite, and kaolin as adsorbents for reducing the adverse impacts of mycotoxin contaminated feed on broiler histopathology and hemato-biochemical changes. *Vet. World* 2021, 14, 23–32. [CrossRef]