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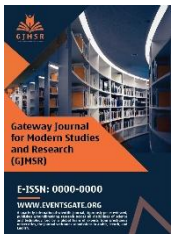

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Using Beneficial Lactic Acid Bacteria to Remove or Inhibit Ochratoxin A from Foods : Review

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Abstract: Ochratoxin A (OTA) is one of the most potent and global mycotoxins, primarily produced by the Aspergillus and Penicillium fungi. Its presence in different cereals, coffee, wine, and dairy products remains a global public health and food security concern. Besides, traditional decontamination techniques (physical and chemical) may be ineffective, highly expensive, and cause significant changes in the nutrition and the sensory attributes of the products. Over the last few years, biological detoxification has proven to be the most dependable, cost-effective, and environmentally safe method. In particular, lactic acid bacteria (LAB) can reduce fungal growth and detoxify OTA through cell-wall adsorption, enzymatic biotransformation, and inhibition of fungal growth. This article reviews OTA contamination, the consequences of mycotoxin poisoning, and established regulatory parameters for detoxification before detailing the mechanisms employed by LAB to detoxify across different food matrices. The detoxification mechanisms are influenced by strain, detoxification parameters, and the environment, all of which are thoroughly explained. The review also outlines the obstacles and safety issues surrounding the LAB detoxification approach in food industrialization, as well as the anticipated developments in this area. Growing evidence supports the ongoing, safe biological actions of LAB against OTA contamination as effective biocontrol agents and sustainable, dependable biocontrol practitioners. This becomes an important improvement in global food safety.

Keywords: Ochratoxin A; Lactic Acid Bacteria; Mycotoxin Detoxification; Adsorption; Food Safety; Probiotics.

1. Introduction

Mycotoxins are secondary metabolites produced by different filamentous fungi, particularly Aspergillus, Penicillium, and Fusarium genera (Ben Miri et al., 2024; Lee, 2024). As global threats to food safety, animal health, and the economy, these mycotoxins cross-contaminate agricultural products at pre-harvest and post-harvest levels (Kos et al., 2023). Ochratoxin A (OTA) is one of the most toxic and widely found mycotoxins among hundreds of mycotoxins (Fuchs et al., 2008; Chen et al., 2018). OTA consists primarily of production by A. ochraceus, A. carbonarius, and P. verrucosum and occurs in various food sources, including cereals, coffee, dried fruits, wine, beer, and dairy (Taheur et al., 2022). Its stability hinders attempts to remove OTA in numerous food-

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processing activities. OTA is heat-stable at moderate temperatures, resistant to the action of certain acids, and stable to light, thereby enabling its survival during cooking, roasting, and even fermentation (Biru & Tassew, 2019; Heintz et al., 2021). Based on the above argument, managing both acute and chronic toxic effects of OTA is important for handling OTA in foods.

It shows some severe toxic effects on the kidneys, liver, and immune system, and can also induce developmental and reproductive abnormalities, and neoplasms in human and nonhuman organisms (Yang et al., 2024; Luz et al., 2018). Consequently, the European Food Safety Authority and the World

The Health Organization has imposed highly restrictive maximum permissible limits on OTA concentrations in food and feed (Lee et al., 2024). Regarding the OTA issues, the so-called 'decontamination' methods, including heat treatment, chemical oxidation, and physical adsorption, are unhelpful (Ferreira et al., 2021). Although they may be able to lower the OTA concentration, they may also alter the food in undesirable ways. Finally, inappropriate costs, disproportionate effort, and lack of scalability are traits that make these methods unhelpful at an industrial level (Ahmad et al., 2024). This is why there is great interest in methods that are safe, effective, and environmentally friendly for controlling OTA.

Mycotoxin degradation, absorption, and transformation into less-toxic forms using microorganisms and their metabolites are active areas of research (Chen et al., 2018; Muhialdin et al., 2020). When examining the alternatives, particular microorganisms of choice, lactic acid bacteria (LAB), are detoxifying microorganisms of note, GRAS, Generally Recognized As Safe. (Rahman et al., 2025; Luz et al., 2018). Various species of the LAB, especially *Lactobacillus plantarum, L. rhamnosus, L. brevis, and L. casei,* detoxify OTA through adsorption in the cell wall and intercellular enzymatic degradation of OTA to non-toxic metabolites of ochratoxin α (OTα) plus phenylalanine (Piotrowska, 2014; Moncalvo et al., 2018).

In addition to their detoxifying action, LAB play a protective role in food systems by competing with and inhibiting the growth of OTA-producing filamentous fungi through the production of organic acids and antimicrobial peptides (Guan et al., 2023; Krantar et al., 2025). Integrating LAB into food processing systems, whether as starter cultures, probiotics, or surface treatments, provides a biotechnological solution to the OTA problem in the food supply (Ben Miri et al., 2024; Khan et al., 2025).

This review seeks to describe lactic acid bacteria as a means of detoxifying and controlling OTA contamination in food. This examines the incidence and toxicology of OTA, the detoxification mechanisms employed by LAB, their uses in different food matrices, and the associated safety issues. Furthermore, the emerging challenges and research gaps are presented to inform the future development of more efficient biological control methods targeting OTA in the international food supply.

2. Occurrence and Toxicity of Ochratoxin A

Ochratoxin A (OTA) is one of the most common and persistent mycotoxins along the food chain worldwide. It is chiefly generated by four fungi: *Aspergillus ochraceus, A. carbonarius, A. niger, and Penicillium verrucosum*. These four fungi can colonize a range of crops under humid, moderately warm conditions (Taheur et al., 2022; Ben Miri et al., 2024). Contamination starts in the field, at harvest, or in storage conditions if the moisture is above 13% and the temperature is in the 20-30 °C range (Heintz et al., 2021). OTA contamination has been repeatedly identified in several cereals (i.e., wheat, maize, barley, oats) and numerous other products, including coffee, cocoa, dried fruits, spices, wine, beer, and meat and dairy products (Ahmad et al., 2024). OTA is also persistent through various food processing practices (e.g., roasting, baking, and fermentation)

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and, as a result, it is nearly impossible to eliminate once it has contaminated the food chain (Biru & Tassew, 2019; Lee et al., 2024).

The unique physicochemical stability of OTA can be attributed to the amide bond that links L-phenylalanine to the rest of its structural components, including a chlorinated dihydroisocoumarin moiety (Yang et al., 2024). Given this structural configuration, OTA also withstood high pest temperatures and acidic conditions (Ferreira et al., 2021). More than 90% of OTA's initial concentration stands to be retained even after the most extreme roasting process of coffee as well as the baking of bread (Ben Miri et al., 2024). As a result, even after completion, consumer products continue to contain contaminants (Kos et al., 2023).

Biologically, OTA has a nephrotoxic effect primarily on the proximal renal tubules and interstitial tissue and is associated with Balkan Endemic nephropathy (BEN) and chronic nephritis (Luz et al., 2018; Yang et al., 2024). It is also immunosuppressive, hepatotoxic, carcinogenic, and teratogenic, which classifies it as a Group 2B carcinogen by the International Agency for Research on Cancer (IARC) "possible carcinogenic to humans" (Lee et al., 2024). Due to the toxin's long biological half-life, chronic exposure, even at trace concentrations, can produce cumulative toxic effects as the toxin remains in plasma, interstitial tissues, and organs (Luz et al., 2018; Mazur-Kuśnirek et al., 2024).

Due to its public health repercussions, OTA contamination also creates large economic impacts, especially in the global trade of coffee, cereals, and wine (Taheur et al., 2022; Ahmad et al., 2024). Merchants have their exports denied if the OTA concentration surpasses the safety limits set by global entities. The EU has established maximum limits of 3 µg/kg for cereal products, 5 µg/kg for roasted coffee beans, and 0.5 µg/kg for infant foods (Ben Miri et al., 2024). The WHO and FAO suggest keeping the tolerable weekly intake (TWI) below 120 ng/kg body weight (Yang et al., 2024). These data indicate the need for safe and sustainable control strategies for OTA across the production and storage chains.

OTA continues to rank among the most difficult foodborne contaminants to control due to its prevalence, potential for harm, and resilience. Therefore, research has shifted towards the biological detoxification of the contaminant via lactic acid bacteria (LAB) for the first time. This is due to their natural occurrence in food systems, their documented capacity as biological control agents against OTA-producing fungi, and their ability to adsorb or degrade the mycotoxin (Chen et al., 2018; Muhialdin et al., 2020; Krantar et al., 2025).

3. Biological Detoxification Approaches for Ochratoxin A (OTA)

Over the last 20 years, research has focused on developing tools to either eliminate or reduce the concentration of Ochratoxin A (OTA) in contaminated food and feed (Taheur et al., 2022; Ben Miri et al., 2024). Detoxification techniques can be classified as biological, physical, or chemical, each with distinct mechanisms and advantages and disadvantages (Lee et al., 2024). In terms of chemical techniques, targeted approaches aim to neutralize, modify, or remove chemical constituents that reduce OTA occurrence in food.

Biological approaches involve the use of microorganisms and/or the targeting of humic acid designed for pyrolysis, followed by the targeted removal of ochratoxin A from highly contaminated cells.

3.1. Physical and Chemical Approaches

The control of OTA contamination through physical methods, including adsorption, sorting, irradiation, and thermal processing, has been documented. The use of adsorbents such as activated charcoal, zeolites, bentonite, and chitosan has been reported to bind to OTA and reduce its

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bioavailability (Ahmad et al., 2024; Heintz et al., 2021). Nevertheless, such methods tend to be ineffective in complex food matrices (e.g., dairy products and beverages) (Biru & Tassew, 2019) because they are inefficient, deplete nutrients, and require large amounts of adsorbents.
Roasting and baking do result in partial degradation of OTA; however, neither appears to eliminate it, as OTA is heat-stable (Yang et al., 2024; Ben Miri et al., 2024). In a laboratory setting, chemical detoxification methods (ozone, hydrogen peroxide, sodium bisulfite, ammonization) also detoxify and/or destroy the OTA molecule (Fuchs et al., 2008). These methods, while effective, may also lead to adverse effects, such as by-products, changes in the product's sensorial profile, and/or the risk of poisoning (Kos et al., 2023; Ferreira et al., 2021). This is the primary reason why chemical detoxification is not encouraged, particularly at a large scale and for products destined for human consumption (Lee et al., 2024).
From a practical point of view, the integration of physical and chemical methods is driven by the lack of comprehensive methodologies that meet the OTA management criteria for safety and the required ecological and holistic balance (Taheur et al., 2022).

3.2. Biological Detoxification as a Promising Alternative

Unlike traditional methods, biological detoxification uses living organisms as biological agents for detoxification, offering ingenious, fully sustainable, reliable, and socially acceptable approaches (Chen et al., 2018; Muhialdin et al., 2020). Adsorption, biotransformation, and biodegradation can all neutralize mycotoxins. In biological detoxification methods, the organisms that perform detoxification are microorganisms (bacteria, yeasts, or fungi), along with their enzymes. Biological methods are also inexpensive due to lower operational and environmental costs and improved food preservation (Rahman et al., 2025).

Among the different types of microorganisms, Lactic Acid Bacteria (LAB) have the greatest potential for OTA detoxification. Their integration into food systems is made possible by their safety (GRAS/QPS status), natural presence in fermented foods, and probiotic activity (Luz et al., 2018; Rahman et al., 2025). The mechanisms by which LAB diminish OTA contamination include the following: Non-covalent binding of OTA to peptidoglycan, teichoic acids, and cell surface proteins, wherein OTA is trapped by adsorption.

1. The action of hydrolytic carboxypeptidase and amidase-type enzymes that degrade OTA into the less toxic ochratoxin α (OTα) and phenylalanine (Piotrowska, 2014; Moncalvo et al., 2018).
2. The lactic and acetic acids, hydrogen peroxide, and antifungal peptides (bacteriocins) that they produce, which inhibit OTA-producing fungi (Guan et al., 2023; Krantar et al., 2025).

In vitro studies have shown that across different studies, varying factors such as bacterial strain type, pH, temperature, and the viability status (living, dead, or free/immobilized) of bacterial cells have a considerable influence on the efficiency of OTA removal (Ben Miri et al., 2024; Khan et al., 2025). For instance, lactobacillus strains L. rhamnosus and L. casei reduced OTAs by 40 to 90 percent, with no significant effect on the food's sensory characteristics (Luz et al., 2018; Moncalvo et al., 2018). Also, the reusability of LAB cells with encapsulated/immobilized cells and their stability in different industrial settings are documented to be better (Krantar et al., 2025).

3.3 Comparative Advantages of the Biological Methods

Biological detoxification, unlike physical and chemical methods, not only reduces OTA levels but also improves the food by providing antifungal and antioxidant properties (Ahmad et al., 2024; Rahman et al., 2025). LAB detoxification is selective and non-destructive, thus preserving the food nutrients and the sensory properties. Also, the by-products of metabolism, such as OTα, would

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have no toxic or detrimental effects on the environment and thus be harmless (Piotrowska, 2014; Yang et al., 2024).

Continuation of in vivo and industrial applications standardization is ongoing (Taheur et al., 2022; Khan et al., 2025). Upcoming research focuses on identifying key OTA-degrading enzymes, refining fermentation parameters, and confirming the efficacy of LAB on pilot and industrial scales (Muhialdin et al., 2020; Rahman et al., 2025).

4. Interactive Mechanisms of Ochratoxin A Removal Employing Lactic Acid Bacteria

Detoxification of Ochratoxin A (OTA) using lactic acid bacteria (LAB) is explained in terms of two mechanisms, i.e., adsorption of the toxin by the bacterial cell walls and the enzymatic degradation of the toxin into less toxic forms by the bacterial cells (Piotrowska, 2014; Chen et al., 2018). Whether the mechanisms operate in a given case depends on the specific LAB strain used and the environmental conditions surrounding the cells, including pH, temperature, and cell viability (Ben Miri et al., 2024). The specific conditions for the mechanisms are relevant to determining the extent to which LAB can be used to detoxify a food and the food's probable safety afterward (Rahman et al., 2025).

4.1 The Mechanism of Adsorption (Binding to Cell Wall Components)

As established by Moncalvo et al. (2018) and Ahmad et al. (2024), adsorption is the fastest and most important mechanism by which LAB performs detoxification. OTA toxin molecules physically bind to the bacterial surface without destruction (Taheur et al., 2022). Adsorption involves non-covalent interactions in which bonding forces may be electrostatic, hydrogen-bonding, or hydrophobic (Biru & Tassew, 2019).

Layers of the LAB cell walls contain and bind OTA from the peptidoglycan, teichoic, lipoteichoic, surface, and exopolysaccharide (EPS) proteins (Heintz et al., 2021). Carboxyl and amino groups, as well as other functional groups that serve as active bonding sites for OTA (Luz et al., 2018), promote further OTA adsorption. OTA is also hydrophobically attracted to the bacterial surfaces, which have non-polar regions and adsorbed hydrophobic aromatic rings of OTA (Yang et al., 2024).

In vitro studies show that adsorption capacity varies across bacterial strains and with cell viability. *Lactobacillus rhamnosus* GG and L. plantarum V22 possess robust OTA-binding capabilities, with removal efficiencies exceeding 80% under optimal circumstances (Rahman et al., 2025; Khan et al., 2025). Remarkably, inactivated or heat-killed cells exhibit similar adsorption activity, suggesting that it is the cell-wall structure, rather than the cells' biochemical activity, that drives binding (Ben Miri et al., 2024; Krantar et al., 2025). Consequently, this characteristic makes adsorption safe for industrial use, as the dead cells can be incorporated into non-fermented foods. The process of binding, however, can be somewhat dissociated, particularly under acidic conditions or at high salt concentrations (Ferreira et al., 2021). This indicates the need for process optimization to prevent desorption during detoxification intended for storage or use in gastrointestinal probiotic formulations (Taheur et al., 2022).

4.2 Enzymatic Degradation (Biotransformation of OTA)

In addition to surface adsorption, some strains of Lactic Acid Bacteria (LAB) can enzymatically degrade OTA into less harmful products (Piotrowska, 2014; Moncalvo et al., 2018). This biotransformation involves hydrolysis of the amide bond linking L-phenylalanine to the isocoumarin moiety, yielding ochratoxin α (OTα) and phenylalanine (Chen et al., 2018). OTα is non-toxic and can be easily eliminated from the body and, therefore, can be considered a safe endpoint for detoxification (Rahman et al., 2025).

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The enzymes involved, be they extracellular or surface-bound, include carboxypeptidases, amidases, and proteases (Yang et al., 2024; Ahmad et al., 2024). Lactobacillus brevis and L. acidophilus demonstrate notable OTA-degradation capacity, especially within the near-neutral pH range of 6.0–7.0 and moderate temperature range of 30–37 °C (Luz et al., 2018; Ben Miri et al., 2024). Certain LAB strains demonstrate a broad spectrum of detoxifying potential by producing multifunctional enzymes that degrade other mycotoxins, such as zearalenone and aflatoxin B1 (Guan et al., 2023; Krantar et al., 2025).

Enzymatic OTA detoxification differs significantly from adsorption; it is irreversible because the OTA molecule's chemical structure is modified (Chen et al., 2018). For this reason, biotransformation is of great value for long-term safety concerning products with the strictest contamination thresholds, such as infant foods and probiotic supplements (Taheur et al., 2022).

Microscopic view of *Aspergillus* ochraceus (Rubin, 2023) | *Penicillium verrucosum* (BIONTE Technical Department, 2023) | *Asrgungus carbonarius* (Visagie et al., 2014)

Figure 1. Interaction between *Aspergillus* and *Penicillium* species producing Ochratoxin A (OTA) and lactic acid bacteria (*Lactobacillus* spp.), binding and degrading the toxin.

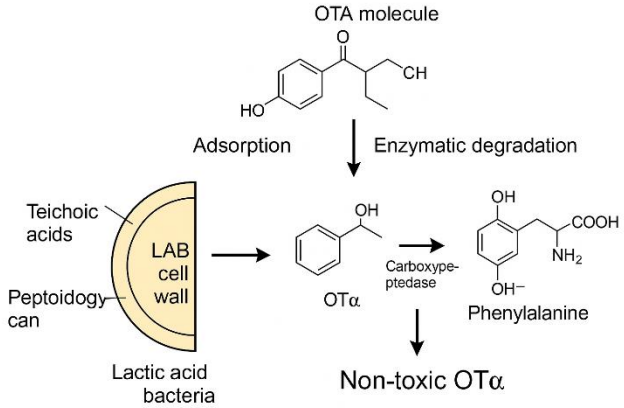

Figure 2. Mechanisms of Ochratoxin A (OTA) Detoxification by Lactic Acid Bacteria.

4.3 Factors Influencing the Efficiency in Removing OTA

Multiple factors influence how efficiently LAB eliminates OTA (Rahman et al., 2025):

- Bacterial strain and cell concentration — Different LAB species have differing and variable capacities for binding and degrading OTA. Higher cell densities also influence the rate of removal (Ahmad et al., 2024).
- Cell viability, OTA removal can be accomplished by both metabolically inactive and active cells. However, only metabolically active cells can degrade the toxin and perform the necessary cellular enzymatic function (Ben Miri et al., 2024).

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- pH and temperature Optimal detoxification occurs in the 6-7 pH and 25-37 °C temperature ranges (Luz et al., 2018; Yang et al., 2024).
- Contact time and incubation. Detoxifying agents facilitate the removal of OTA until adsorption equilibrium is reached, which occurs within a few hours (Taheur et al., 2022).
- Matrix composition Proteins, lipids, and other organic materials in the food matrix compete for binding sites with OTA, and potentially influence compliance (Ferreira et al., 2021).
- Surface modifications - As indicated by the surface charge, treatments such as heat inactivation, acid washing, and enzymatic stripping can substantially alter the OTA-binding affinity (Khan et al., 2025).

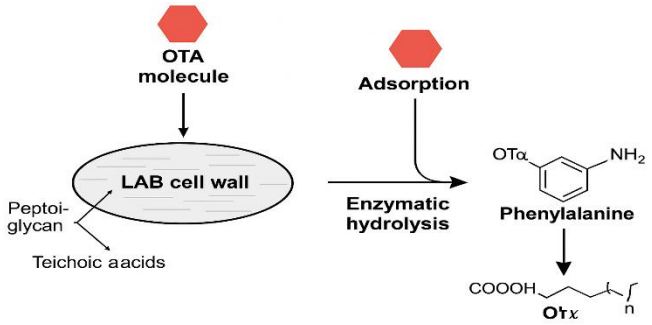

Figure 3. Factors Influencing Ochratoxin A (OTA) Removal Efficiency by Lactic Acid Bacteria.

5. Uses of Lactic Acid Bacteria in Various Food Interfaces.

The practical uses of lactic acid bacteria (LAB), specifically for the removal or inhibition of Ochratoxin A (OTA), have recently been documented across a variety of food matrices (Taheur et al., 2022; Rahman et al., 2025). This is due to their safety (GRAS/QPS status), metabolic versatility, and ability to function in both fermented and non-fermented products (Luz et al., 2018; Ben Miri et al., 2024). This makes them reliable in food processing.

This section addresses primary food matrices—dairy, cereals, beverages, and animal feeds—that use lactic acid bacteria (LAB) to detoxify ochratoxin A (OTA), focusing on the extent of detoxification, food safety, and the maintenance of organoleptic quality (Ahmad et al., 2024).

5.1 Dairy Products (Milk, Cheese, Yogurt)

OTA detoxification in dairy systems is promising due to the prevalence of lactic acid bacteria (LAB), the importance of fermentation, and system dependence (Ben Miri et al., 2024). OTA contamination of the dairy system occurs through contaminated animal feed, and the feed-milk-cheese transit lines can also transport OTA (Kos et al., 2023). *Lactobacillus rhamnosus, L. plantarum, and L. casei* reduce OTA levels in milk-based products by means of adsorption and enzymatic degradation (Piotrowska, 2014; Moncalvo et al., 2018).

In fermented milk and yogurt, while mitigating the effects of ochratoxin A (OTA), lactic acid bacteria (LAB) inhibit the growth of Aspergillus ochraceus and Penicillium verrucosum, which produce OTA (Guan et al., 2023). Reported reductions of OTA of 60-90% occur within the first 24 hours of fermentation (Rahman et al., 2025). Also, heat-inactivated LAB have effectively served as biodegradable sorbents in pasteurized milk, continuously deactivating OTA for prolonged periods while maintaining the milk's taste, color, and texture (Krantar et al., 2025).

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5.2 Cereal-Based and Bakery Products

Cereal grains are a major source of ochratoxin A (OTA) worldwide (Taheur et al., 2022). The use of LAB in the fermentation of cereal products, including bread, sourdough, and breakfast cereals, has been shown to reduce OTA (Yang et al., 2024; Ahmad et al., 2024). The main mechanism by which LAB cells attenuate OTA is through the adsorption of OTA to the cell wall during fermentation, although some enzymatic hydrolysis may occur (Chen et al., 2018; Moncalvo et al., 2018).

Fermentations with L. plantarum V22 and L. brevis resulted in an 85% reduction in OTA while preserving desirable dough texture and bread volume (Luz et al., 2018). Detoxification is enhanced in the presence of co-fermenters, Saccharomyces cerevisiae, due to synergistic enzymatic activities and the production of organic acids (Rahman et al., 2025). In addition to toxin removal, fermentation with lactic acid bacteria (LAB) improves food taste, enhances shelf life, and increases the bioavailability of important nutrients (Khan et al., 2025).

5.3 Wines, Beverages, and Juices

OTA contamination in grape-derived beverages, especially wine, is caused by Aspergillus carbonarius and A. niger and is a problem during vineyard storage and processing (Ben Miri et al., 2024). During MLF, the combination of *Oenococcus oeni and Lactobacillus plantarum* resulted in strong OTA binding and a 40-70% reduction, while maintaining sensory parameters (aroma, color, and acidity) (Ferreira et al., 2021; Heintz et al., 2021).

L. rhamnosus and L. paracasei in fruit juices, especially grape and apple, effectively adsorbed OTA while maintaining beverage clarity and stabilizing pH (Ahmad et al., 2024; Rahman et al., 2025). Recent advancements include the use of immobilized-cell systems and line or cellulose carriers, which enable continuous removal of OTA during juice storage or filtration (Krantar et al., 2025).

5.4 Animal Feed and By-Products

Exposure of livestock to OTA-contaminated feed poses a twofold risk—toxicity to the animal and transmission to animal products such as milk, meat, and eggs (Taheur et al., 2022). LAB, including L. plantarum, L. pentosus, and Pediococcus acidilactici, have been used as feed additives or probiotic supplements to mitigate OTA bioavailability and enhance gastrointestinal health (Yang et al., 2024; Rahman et al., 2025).

Feeding studies conducted with poultry and swine, as well as other livestock, have shown that the inclusion of LAB or symbiotic derived from LAB substantially reduced OTA concentrations in the plasma and exposed tissues and optimized the histopathological conditions of the liver and kidneys (Luz et al., 2018; Khan et al., 2025). Besides detoxification, LAB possess antioxidant and immunomodulatory activities which enhance the animal's resilience to oxidative stress and infections (Guan et al., 2023). The latter two activities contribute to the economic value of LAB supplementation at this stage in the feed-to-food continuum (Ben Miri et al., 2024).

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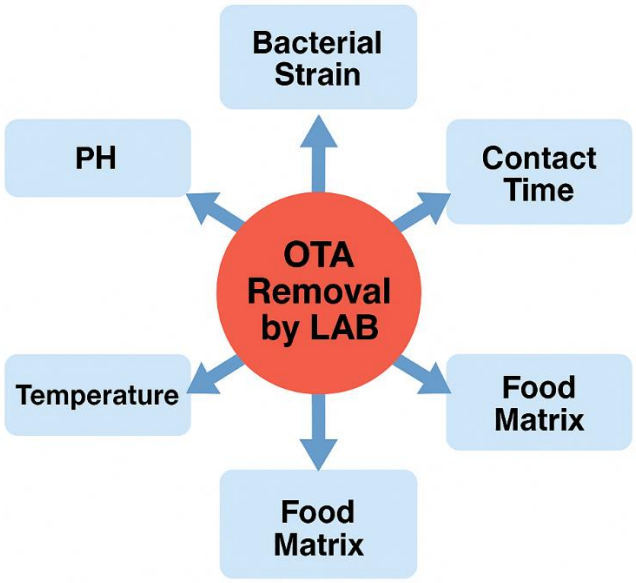

Figure 4. Applications of Lactic Acid Bacteria (LAB) for Ochratoxin A (OTA) Detoxification in Different Food Matrices.

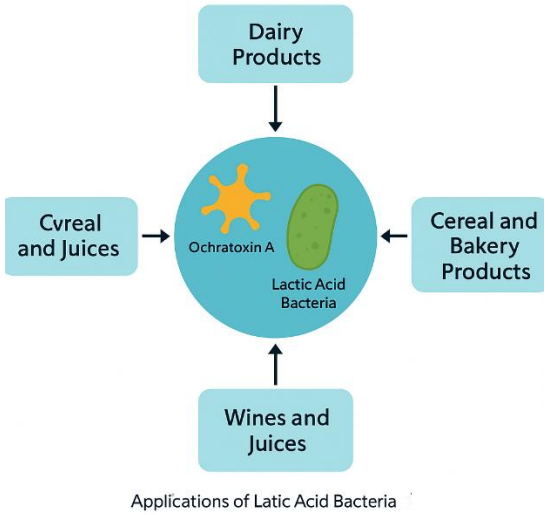

Figure 5. Industrial Workflow of LAB-Based Ochratoxin A (OTA) Detoxification.

6. Industrial Implementation and Technological Considerations

Moving laboratory findings on the detoxification of OTA by lactic acid bacteria (LAB) to the industrial stage requires consideration of appropriate scale, process integration, safety, and regulatory oversight. Although the literature reports detoxification by LAB, few studies have examined this practice in actual production settings (Taheur et al., 2022; Ben Miri et al., 2024).

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6.1 Process Integration in Food Manufacturing

From an industrial perspective, the LAB must withstand and function under specific controlled production conditions of varying temperatures, air exposure, and mechanical product stirring (Rahman et al., 2025). Successful integration, whether as a starter culture, adjunct probiotic, or immobilized biocatalyst, is dictated by the formulation (Piotrowska, 2014; Moncalvo et al., 2018). Cell immobilization using alginate, carrageenan, or cellulose matrices enhances cell stability while enabling continuous OTA removal from liquid foods such as juices, wine, and milk (Krantar et al., 2025).

Advancements have been made in optimizing fermentation techniques with Lactobacillus plantarum and L. rhamnosus to enhance OTA adsorption during short fermentation cycles (Chen et al., 2018; Luz et al., 2018). Adsorption efficiency, along with the bacterial viability under moderate escapement and pH control (6.0-6.5), has been demonstrated in industrial trials (Ahmad et al., 2024). Moreover, incorporating LAB into packaging films or coatings offers a novel approach to active bioprotection, reducing OTA levels and prolonging shelf life (Guan et al., 2023).

6.2 Quality Control and Optimization Parameters

Inconsistent detoxification can be caused by poorly set process parameters such as cell concentration, contact time, and fermentation temperature (Taheur et al., 2022). Continuous variable OTA control and quantification before and after detoxification treatment can be achieved using HPLC–MS/MS or ELISA methods (Heintz et al., 2021). LAB-based detoxification is now included in industrial HACCP's preventive control measures, particularly in coffee, cereals, and wine, as elaborated in Ferreira and Gonzalez (2021).

In pilot-scale fermenters, LAB strains exhibit stable OTA removal efficiencies of 80–90% under optimized agitation and aeration conditions (Rahman et al., 2025). Meanwhile, strain robustness and the preservation of adsorption capacity during downstream processing, such as spray or freeze-drying, still affect the potential for scale-up (Khan et al., 2025).

6.3 Technological Challenges

Although some progress has been made, a few challenges remain to be addressed to carry out full-scale implementation.

- Standardization: The lack of predictability in OTA-binding behavior is a result of the variability present in the different LAB species and even strains within the same species (Yang et al., 2024).
- Desorption risk: Bound OTA may release in part during storage under acidic or high-ionic conditions (Biru & Tassew, 2019).
- Industrial cost: The costs of immobilization materials and process validation may be justified as the improved production cost, in comparison to traditional methods, may be increased (Ben Miri et al., 2024).

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- Sensory compatibility: The color and/or flavor desirability of the final product may be impacted due to high loads of bacteria or fermentation by-products (Kos et al., 2023).

These issues might be tackled by integrating several fields—microbiology, food engineering, and materials science—to develop advanced bioprocesses that meet the necessary safety and profitability objectives (Guan et al., 2023).

6.4 Future Industrial Prospects

The increasing need for clear-label products and environmentally friendly processing is the rationale for using LAB to detoxify OTA in the context of green manufacturing (Rahman et al., 2025). The continued strain engineering and metabolic optimization work for LAB will likely result in increased production of OTA-degrading enzymes and increased industrial stress tolerance (Krantar et al., 2025). Further benefits to the commercial viability of this approach are expected when LAB are coupled with automated fermentation technology and continuous bioreactors (Ahmad et al., 2024).

Lastly, the collaboration between academic research and industry stakeholders will be fundamental to the issuance of standard operating procedures aligned with current EFSA and WHO guidelines (Taheur et al., 2022; Lee et al., 2024). Actively working on validation studies, LAB-based detoxification technology will be positioned as the primary approach for advanced food safety control in the next generation of food safety management.

7. Synergistic Use of LAB with Other Biocontrol Agents

Given the considerable individual detoxification capabilities of lactic acid bacteria (LAB), their detoxification efficacy against Ochratoxin A (OTA) can be further improved when used alongside other biocontrol agents or complementary technologies (Taheur et al., 2022; Rahman et al., 2025). The combined approach, also known as 'synergism,' is gradually becoming the approach of choice in contemporary food safety systems, as it enhances the efficacy of multiple detoxification pathways while preserving the food's sensory and nutritional qualities (Chen et al., 2018; Ahmad et al., 2024).

7.1 Combination with Yeasts

Co-fermentation of LAB with yeasts, specifically Saccharomyces cerevisiae and Candida krusei, has significantly improved OTA degradation through co-operative mechanisms (Moncalvo et al., 2018). They can do this because yeast cells have mannoproteins in their cell walls and therefore adsorb OTA. At the same time, LAB detoxify toxins by degrading them or binding them to peptidoglycan structures, and then secrete them onto cell walls (Luz et al., 2018). In studies with combined fermentations of Lactobacillus plantarum and S. cerevisiae in sourdough and in grape musts, OTA diminutions were over 85 % as opposed to 60–70 % when using either microorganism alone (Ben Miri et al., 2024).

Furthermore, yeast fermentation produces ethanol, organic acids, and carbon dioxide, which modify matrix conditions, leading to OTA solubilization and increased adsorption capacity of LAB

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(Ferreira et al., 2021). Enhancing these attributes improves aroma formation and shelf life, thereby enhancing the commercial viability of this method in the bakery and wine industries (Lee et al., 2024).

7.2 Integration with Other Bacteria and Fungi

In addition to yeast, combinations of certain fungal and bacterial probiotics with no pathogenic potential for LAB have also been investigated to broaden the scope of detoxification (Taheur et al., 2022). The co-cultivation of Lactobacillus casei with Bacillus subtilis or Aspergillus oryzae has been shown to increase OTA-degrading enzyme activity compared to monocultures, which may be due to synergistic secretion of protease and amidase (Guan et al., 2023; Krantar et al., 2025). Furthermore, during solid-state fermentation of cereals, OTA degradation reached nearly 90% while preserving preferred sensory and nutritional attributes using a blended microbial consortium comprising *Pediococcus acidilactici and Rhizopus oligosporus* (Ahmad et al., 2024). These microbial consortia are targeted for large-scale feed detoxification, in which mixed cultures can withstand unstable pH and temperature conditions (Yang et al., 2024).

7.3 Combination with Prebiotics and Natural Adsorbents

With respect to prebiotics, the synergistic concept applies to natural adsorbents that support the growth of LAB or provide additional binding sites (Ben Miri et al., 2024). The addition of inulin, fructo-oligosaccharides (FOS), or β-glucans to the diet of LAB improves cell-wall integrity, thereby helping LAB survive and enhancing adsorption efficiency (Khan et al., 2025). Also, combining LAB with bentonite, zeolite, or activated carbon enables a dual-adsorption system in which the inorganic materials capture the residual OTA that the bacteria have not bound (Ferreira et al., 2021). This reduces the likelihood of toxin release under gastrointestinal conditions and enhances detoxification yield without affecting product quality (Rahman et al., 2025).

The last few years have seen rapid technological growth, providing opportunities to integrate LAB with many non-thermal technologies, especially pulsed electric fields, ultrasound, and cold plasma (Heintz et al., 2021; Guan et al., 2023). These techniques intensify OTA degradation by enhancing bacterial surface permeability and increasing bacterial enzyme activity. For example, cold-plasma pretreatment of L. plantarum increased OTA adsorption by 35% while preserving cell viability (Krantar et al., 2025). Encapsulation using alginates, chitosan, and nanocellulose integrates and safeguards the controlled-release action within versatile matrices, thereby improving stability for the LAB (Taheur et al., 2022; Ahmad et al., 2024). Innovations that bridge bench-scale performance and industrial detoxification systems are paving the way toward more affordable systems.

8. Safety and Regulatory Perspectives

The adoption of lactic acid bacteria (LAB) to control Ochratoxin A (OTA) in food and feed must comply with international safety and legal guidelines to protect consumers and ensure industrial acceptability (Taheur et al., 2022; Lee et al., 2024). Due to the long-standing use of fermentation and probiotics with LAB, various LAB species have gained safety recognition under international

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guidelines, making detoxification systems easier to integrate (Rahman et al., 2025; Ben Miri et al., 2024).

8.1 Safety Status of Lactic Acid Bacteria

LAB strains such as *Lactobacillus plantarum, Lacticaseibacillus rhamnosus, Lactococcus lactis, and Pediococcus acidilactici* have GRAS recognition in the United States and QPS status in the European Union (Ferreira et al., 2021). They have been incorporated into numerous fermented foods, and their absence of pathogenicity, toxin production, and transferable antibiotic resistance has been documented (Luz et al., 2018; Yang et al., 2024). When selected and properly characterized, live and heat-inactivated LAB preparations lack cytotoxic and mutagenic properties (Ahmad et al., 2024; Krantar et al., 2025), which makes them excellent candidates for food detoxification. In addition, LAB detoxification of OTA is particularly important because it avoids the creation of harmful intermediates and chemical residues. As outlined in Moncalvo et al. (2018) and Piotrowska (2014), ochratoxin α (OTα) is harmless and can be excreted quickly. This further confirms that the long-term use of LAB-based treatments is safe for human consumption.

8.2 Mycotoxin Control Regulations

The European Commission currently enforces the following regulations on maximum OTA levels in food products: 3 µg/kg in cereal products, 5 µg/kg in roasted coffee, and 0.5 µg/kg in infant food. Also, the EU Commission sets a maximum limit of 0.03 µg/kg in feed products. The World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations, on the other hand, recommend a tolerable weekly intake limit of 120 ng/kg body weight for roasted coffee. Any detoxification LAB strain or product must fulfill the 3 essential core regulations as outlined by Taheur et al. (2022):

1. The detoxification strain is taxonomically identified and approved for use in that specific food industry.
2. The detoxification improves or, at the very least, retains the sensory or nutritional value of the food.
3. The detoxification products are stable, non-toxic, and can be quantified.
1. These guidelines, outlined by Ben Miri et al. (2024), must be adhered to in order to obtain approval from the EFSA, FDA, and other similar governing bodies associated with Regional Food Safety.

8.3 Consumer and Technology Issues

Regarding processed products, the use of the LAB detoxification technique should still comply with Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP) (Heintz et al., 2021). For this technology to be used in the market, the detoxification system's reproducibility, sensory and microbial safety, and the strain's detoxification stability must be validated (Ahmad et al., 2024). For consumers, the growing demand for products marketed as “clean-label” and eco-friendly supports the use of natural microbial alternatives over synthetic ones (Rahman et al., 2025). Research indicates that with proper labeling and a robust regulatory framework, customers, especially for probiotic or bio-based products, perceive these products as safer and more sustainable (Guan et al., 2023).

8.4 Challenges and Gaps in the Regulatory Framework

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Even with the progress made, there are still issues in the detoxification of OTAs with LAB that must be resolved before full regulatory approval can be obtained (Ben Miri et al., 2024). Due to varying detoxification effectiveness across different strains and food matrices, the development of standard operating procedures is challenging (Yang et al., 2024). The lack of thorough, comprehensive toxicological assessments of LAB metabolites and residual enzymatic activities remains problematic (Ferreira et al., 2021). Current guidelines lack the appropriate focus to assess detoxification processes because most are designed for chemical and physical treatments (Taheur et al., 2022). Global harmonization requires unified testing procedures, validated analytical methods, and internationally accepted risk assessment frameworks (Lee et al., 2024; Rahman et al., 2025).

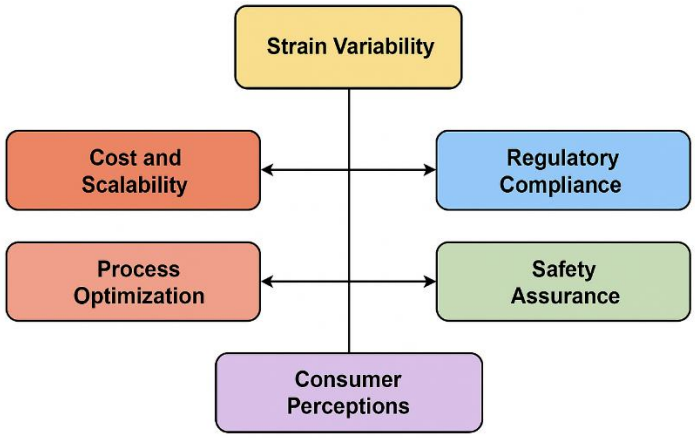

Figure 6. Challenges in Integrating LAB-Based Ochratoxin A (OTA) Detoxification into the Food Industry.

9. Future Perspectives and Research Gaps

Lactic acid bacteria (LAB) have shown potential to detoxify Ochratoxin A (OTA), but their full implementation in industrial and agricultural regulation remains unachieved (Taheur, 2022; Rahman, 2025). Evidence points to LAB as the most profitable microbes for biological detoxification, yet inconsistencies and underdeveloped predictive models pose real-world challenges due to limited in vivo studies and a mechanistic understanding of the detoxification process (Yang, 2024; Ben Miri, 2024).

9.1 Mechanistic Elucidation and Omics-Based Insights

The mechanisms of adsorption and enzymatic degradation have been described functionally, but a complete explanation of their underlying mechanisms remains to be elucidated (Piotrowska, 2014; Moncalvo et al., 2018). Future studies should target the specific genes and pathways involved in OTA degradation utilizing the various omics tools, i.e., genomics, transcriptomics, proteomics, and metabolomics (Chen, 2018; Guan et al., 2023).

As an illustration, comparative genomics may delineate the distribution of amidase-like or carboxypeptidase genes across lactobacilli species. At the same time, transcriptomic studies may indicate that these genes are regulated under stress and during detoxification (Rahman et al., 2025).

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Such molecular understanding is crucial to justify the use of strain engineering and directed evolution methods aimed at improving detoxification (Krantar et al., 2025).

9.2 *In Vivo* Validation and Toxicological Assessment

The majority of the literature focuses on in vitro studies, which are limited in their ability to capture the complex interactions occurring in food matrices and the gastrointestinal tract (Taheur et al., 2022). To ascertain detoxification efficacy, bioavailability, and safety of OTA-degraded products, comprehensive in vivo studies in animal and human models are necessary (Luz et al., 2018; Yang et al., 2024).

In addition, it remains essential to carry out more toxic (toxicokinetics and metabolomics) studies to ascertain that no metabolite of OTA degradation, including OTα, is biochemically active and harmful (Ahmad et al., 2024). Longitudinal studies including livestock and humans should examine possible immunological or microbiota-related consequences of chronic exposure to LAB, which are also important to assess (Ben Miri et al., 2024; Khan et al., 2025).

9.3 Technological Innovation and Scale-Up

The detoxification of OTA using LAB will depend on further evolution in bioprocess engineering and industrial biotechnology. The implementation of continuous fermentation systems and the use of immobilized bioreactors may provide means to improve the scalability and the economic feasibility of the operations (Heintz et al., 2021; Ahmad et al., 2024). The incorporation of nanotechnology and 3D printing into the encapsulation of carrier matrices will further enhance the stability and industrial reuse of the LAB (Krantar et al., 2025; Guan et al., 2023). Future investigations need to focus on integrating LAB detoxification into automated systems that incorporate sensors and AI for real-time OTA monitoring and automated control of production processes (Rahman et al., 2025). Such systems will facilitate traceability, optimal parameter adjustments during fermentation, and control within regulatory frameworks of the global supply chain (Lee et al., 2024).

9.4 Standardization and Global Regulatory Alignment

Insufficient standard evaluation protocols for microbial detoxification remain a considerable hurdle (Taheur et al., 2022; Ferreira et al., 2021). In considering new protocols that focus on detoxification, evaluating the stabilization and safety of residual toxins will require the joint efforts of academic institutions, the private sector, and food safety regulators (Ben Miri et al., 2024). Unified risk-assessment methodologies, covering microbial and enzymatic detoxification, should be harmonized and adopted by the international organizations, EFSA, FAO, and WHO (Lee et al., 2024). This will facilitate harmonized approval processes and increase the global market availability of bio-detoxified products (Rahman et al., 2025).

9.5 Sustainability and Consumer Acceptance

Future inquiries can examine the parts related to the socio-economic sustainability of LB-AD (Chen et al., 2018; Ahmad et al., 2024). Circular bioeconomy concepts can be designed to reduce

waste and improve sustainability, for instance, by using LAB derived from fermented food waste or by recycling detoxification products multiple times (Guan et al., 2023). Consumers' perception is critical too. Consumer acceptance can be achieved through clearly placed, unambiguous, and informative signage, and by communicating sustainability benefits with clinical evidence of safety (Rahman et al., 2025; Khan et al., 2025).

10. Conclusion

Lactic acid bacteria (LAB) have proven to be effective biological agents for reducing and preventing Ochratoxin A (OTA) contamination. However, since most probiotics are recognized primarily for their general health-promoting properties, only a limited number have been specifically characterized as effective biological agents for OTA reduction and prevention in non-specialized feed and food systems. Contaminated feed and food products represent economically significant pathways for OTA entry into the food chain, thereby posing risks to human health. By combining adsorption and enzymatic degradation mechanisms, LAB can significantly reduce OTA levels while preserving the nutritional, sensory, and technological quality of the final products. Furthermore, their natural occurrence in fermented foods and compatibility with food-processing technologies strengthen their potential for industrial-scale application as sustainable biological detoxification agents. Despite these advantages, further research is still required to optimize strain selection, ensure consistency in industrial performance, and standardize biological detoxification processes. In practice, the use of LAB as biological agents for OTA elimination and prevention in feed and food streams is of lower grade and less economically beneficial, as the main profitable grade is the biological detoxification of food. With advances in research and the incorporation of sufficient biological agents for food detoxification, the LAB-based detoxification processes for food contamination will certainly be adopted in developing countries for food safety management, as they rely primarily on the synergistic integration of biological and mechanical detoxification processes.

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