OVERVIEW OF THE POTENTIAL ROLE OF LACTIC ACID BACTERIA IN THE REDUCTION OF MYCOTOXINS AND PESTICIDE RESIDUES IN FOOD AND FEED

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Abstract
Lactic acid fermentation and lactic acid bacteria (mainly *Lactobacillus* and *Streptococcus* species) are widely recognized for their nutritional and health benefits, including the promotion of a balanced gut microbiota, improved digestion, and immune support. Nevertheless, intensive agricultural practices, unauthorized pesticide applications, and inadequate post-harvest and storage conditions frequently result in the occurrence of pesticide residues and mold-derived mycotoxins in crops, feeds and food products. The presence of these contaminants in food and feed poses a major food safety and public health challenge. According to the scientific literature, lactic acid bacteria play a crucial role in the inhibition of pathogens, the neutralization of toxins, and the degradation of chemical contaminants (e.g., pesticide residues). Various mechanisms (e.g., cell wall binding, production of antifungal metabolites, and enzymatic degradation) have been reported to contribute to the direct and/or indirect reduction of mycotoxin and pesticide residue levels. Owing to their broad enzymatic repertoire and diverse beneficial biological activities, lactic acid bacteria constitute a promising natural strategy for the detoxification of food contaminants including mycotoxins and pesticide residues, particularly in the context of large-scale food production and growing environmental pollution.

1. Introduction

The beneficial effects of lactic acid fermentation and lactic acid bacteria are well recognized from both nutritional and health perspectives. During lactic acid fermentation, the presence of lactic acid bacteria (*Lactobacillus* and *Streptococcus* species) can promote the establishment and maintenance of a healthy gut microbiota, positively influence digestion, and strengthen the immune system [1–5]. Nowadays, the extensive use of pesticide formulations in intensive agricultural practices, the application of unauthorized chemicals, as well as inadequately chosen technological conditions during harvest and storage of crops, can substantially contribute to the occurrence of pesticide residues and mycotoxins produced by various molds in agricultural commodities and food products. The presence of mycotoxins and pesticide residues in food and feed poses significant food safety and public health risks. The pesticide active ingredients used in chemical plant protection, often persist throughout food processing, whereas mycotoxins (naturally occurring fungal secondary metabolites) generally exhibit remarkable stability and resistance to degradation [6–7]. Both contaminant groups are associated with severe adverse health outcomes, including carcinogenic, neurotoxic, immunotoxic, and endocrine-disrupting effects [7–9]. In response, stringent regulatory thresholds have been established by international and national authorities. Currently, the conventional mitigation strategies (e.g., chemical decontamination and physical removal) are often costly, not permitted by law, or incompatible with the principles of sustainable food production [10–11]. Lactic acid bacteria have been shown to exert multiple detoxification functions, including the inhibition of pathogenic microorganisms, the neutralization of toxic metabolites, and the biotransformation of xenobiotic compounds [1, 5, 12–17]. Their diverse enzymatic repertoire and metabolic versatility, lactic acid bacteria can serve as a promising biotechnological tool for the detoxification of food containants in the context of industrial-scale production and increasing environmental pollution [1].

2. The role of lactic acid bacteria in the reduction of pecticide residues and mycotoxins

Lactic acid bacteria can contribute to the reduction of pesticide residues and mycotoxins in food and feed, providing a natural strategy that supports the food industry's sustainability objectives by reducing dependence on synthetic chemicals. Based on the results of the published studies, lactic acid bacteria are capable of mitigating residues of various pesticides including herbicides, fungicides, and insecticides (e.g., DDT, chlorpyrifos, malathion) as well as mycotoxins (e.g., aflatoxin B1, ochratoxin A, sterigmatocystin, and patulin) [1, 5, 12–19]. A remarkably wide range of mechanisms is reportedly involved in the reduction of pecticide residues and mycotoxins. The underlying mechanisms include: enzymatic degradation of contaminants, environmental modulation with synergistic effects, metabolic transformation, antioxidant activity and preventive effects, biofilm formation facilitating enhanced detoxification, adsorption through cell wall binding, and production of antifungal metabolites respectively the given food contaminants [1, 13–14, 20–23].

2.1. The potential for mycotoxin reduction by lactic acid bacteria

Mycotoxins are toxic secondary metabolites produced by fungi (e.g., *Aspergillus, Fusarium*, and *Penicillium* species) that contaminate agricultural products such as nuts, fruits, grains, and wine. They may develop in the field, post-harvest, or during processing and storage. Major representatives include aflatoxins, deoxynivalenol, zearalenone, ochratoxin, fumonisin, and patulin, all of which pose significant food safety and public health risks. Mycotoxins are associated with serious health risks, including carcinogenic, hepatotoxic, nephrotoxic, immunotoxic, and neurotoxic effects. Due to the high stability of mycotoxins against heat and conventional processing methods, the prevention and detoxification are particularly challenging [1, 7, 24].

The main direct and indirect mechanisms are involved in the reduction of mycotoxins:

- cell wall binding (non-covalent adsorption onto bacterial surface structures) [15]
- biological degradation (enzymatic breakdown into less toxic metabolites) [25]
- production of antifungal metabolites (inhibition of the growth of molds/other fungi) [23]
- biofilm formation (biofilms increase binding surfaces and environmental resistance to ensure effective detoxification) [26]

Lactic acid bacteria mitigate mycotoxin contamination through multiple mechanisms, including cell wall binding (e.g, aflatoxin B1), production of antifungal metabolites (e.g., 52–80% transcriptional inhibition of the *omt-A* gene responsible for the biosynthesis of aflatoxin B1), enzymatic degradation (e.g., >90% degradation of ochratoxin A by proteolytic activity), and modulation of fermentation conditions (e.g., pH, temperature). Both live and dead cells are effective, and biofilm formation further enhances detoxification by increasing binding surfaces and environmental stability [15, 23, 25–26]. Due to the these beneficial properties of lactic acid bacteria serves as a safe and sustainable strategy for natural food preservation and mycotoxin reduction in food and feed.

2.2. The potential for the reduction of pesticide residues by lactic acid bacteria
Pesticide formulations including insecticides, fungicides, and herbicides are widely used during the intensive agricultural practice to enhance crop yield and quality by controlling pests, diseases, and weeds [8]. The implications of pesticide use in food production, coupled with the recognition that residues may remain in consumable products, are of critical importance for food safety and are a growing concern among health-conscious consumers [27–28]. Additionally, the use of multiple agents on the same commodity can lead to the presence of multiple residues within a single product [29]. The residues of pesticide formulations are associated with a wide spectrum of health risks, encompassing both acute and chronic health effects and risks (e.g., cardiovascular and respiratory diseases, cancer, and endocrine disruptions) [27–29].

The main direct and indirect mechanisms are involved in the reduction of pesticide residues:
- enzymatic breakdown (specific enzymes catalyze the decomposition of pesticides) [21]
- environmental modulation synergistic effects (acidic environments destabilize the pesticide molecules) [14]
- metabolic transformation (convert compounds into less toxic/inactive forms) [12, 21]
- antioxidant effects and proactive action (mitigating oxidative damage associated with pesticide residues) [21]
- biofilm formation (more effective immobilizazion and degradation of pesticides) [21]

Lactic acid bacteria can degrade pesticides through multiple mechanisms, including enzymatic breakdown (e.g., dimethoate, parathion methyl, trichlorfon by phosphatase and antioxidation), metabolic transformation, and biofilm formation, which increase their detoxification capacity (e.g., biofilm-associated lactic acid bacteria can show enhanced degradation efficiency for organophosphorus pesticides compared to planktonic cells). Additionally, environmental modulation (e.g., enhanced deagradation of λ-cyhalothrin, malathion, chlorpyrifos-methyl at low pH) and synergistic interactions further enhance the efficiency of lactic acid bacteria-mediated pesticide degradation in foods and beverages [1, 12, 14, 21, 30].

3. Advantages and limitations of lactic acid bacteria-based reduction approaches
Lactic acid bacteria offer several advantages as biological tool for pesticide and mycotoxin detoxification and reduction. Lactic acid bacteria are non-pathogenic and in many cases probiotic, making them highly suitable for application in foods and feeds [1–5]. Lactic acid bacteria-based strategies provide a sustainable alternative to chemical treatments while simultaneously conferring dual benefits, such as improving nutritional value, extending shelf-life, and enhancing the sensory properties of products [31–32]. Moreover, these microorganisms can be easily integrated into existing fermentation processes and silage production, supporting scalability in both food and feed systems [33]. However, despite the promising results, significant limitations remain. The efficiency of detoxification is highly strain-specific, meaning that not all lactic acid bacteria exhibit the same capability to degrade or bind contaminants (e.g., fumonisins) [34]. Furthermore, matrix effects, such as food composition and processing conditions, strongly influence detoxification performance. Stability is also a concern, as adsorption processes may be reversible, raising questions about the long-term effectiveness of toxin removal [35]. Finally, the mechanistic understanding of lactic acid bacteria detoxification remains incomplete, and further research into enzymatic pathways and genetic determinants is essential to optimize their use in food safety applications.

4. Conclusion

The presence of pesticide residues and mycotoxins in food and feed represents a major global food safety issue. Lactic acid bacteria provide a promising, natural, and sustainable tool for reducing pesticide residues and mycotoxins, while also contributing to gut health and overall well-being. Their detoxification ability through mechanisms related to adsorption, enzymatic degradation, and fermentation is increasingly supported by scientific evidence. Although challenges remain regarding strain specificity, stability, and scalability, lactic acid bacteria-based detoxification can complement or partially replace conventional chemical methods, contributing to safer food systems, improved public health, and more sustainable agricultural practices. Future research should focus on advancing biofilm-based applications, genomic and proteomic screening for high-performing strains, the use of mixed microbial cultures, and pilot-to-industrial scale validations to fully realize the potential of lactic acid bacteria in food and feed detoxification [26, 36].

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