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Biological Control for Food Safety
A Review

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Introduction

The widespread presence of foodborne pathogens and their potential to harm human health remain significant global issues. According to the World Health Organization (WHO), around 600 million instances of foodborne illnesses arise each year, leading to approximately 420,000 fatalities worldwide. These harmful microorganisms, including bacteria like *Salmonella*, *Escherichia coli*, *Listeria monocytogenes* and *Campylobacter*, are accountable for causing various conditions, ranging from mild stomach issues to severe and occasionally lethal infections (CDC, 2020).

Conventional methods of controlling foodborne pathogens concerns regarding the development of antimicrobial resistance, environmental pollution, and potential adverse health effects. In this context, biological control has emerged as a promising strategy, it involves the use of living organisms or their natural products to suppress the growth, reproduction, or survival of target pests or pathogens. This approach relies on the natural ecological interactions that exist within microbial communities and designed to be specific, minimizing non-target effects and preserving beneficial microorganisms.

Methods of Biological Control

Biological control methods harness natural interactions between microorganisms to mitigate the growth and impact of foodborne pathogens.

1. **Bacteriophages:** Bacteriophages, often referred to as phages, are naturally occurring viruses that target and infect specific bacterial hosts. They have gained significant attention as potential biological control agents against foodborne pathogens due to their remarkable specificity and ability to effectively lyse bacterial cells. The mode of action of bacteriophages involves their attachment to specific receptors on the bacterial surface, followed by the injection of their genetic material into the host cell. This leads to the replication of phage particles and the eventual lysis of the bacterial cell, releasing new phage progeny to continue the infection cycle. In the context of food safety, bacteriophages offer several advantages. They are self-replicating, meaning that a small initial dose can lead to exponential amplification in the presence of target bacteria. This amplification can aid in reducing pathogen levels in food products.
   Furthermore, phages have low inherent toxicity and also highly specific, targeting only the host bacterial species without affecting non-pathogenic microorganisms. Additionally, they can be applied directly to food surfaces or incorporated into antimicrobial coatings on food packaging materials, providing a targeted and localized approach to pathogen control (Hudson et al., 2005 ; Kazi et al., 2016).
2. **Probiotics**: Probiotics are live microorganisms that confer health benefits to the host when administered in adequate amounts. They play a vital role in maintaining gut microbial balance and promoting digestive health. In the context of food safety, probiotics have shown potential in inhibiting the growth of pathogenic bacteria through multiple mechanisms. One key mechanism is competitive exclusion, where probiotic microorganisms compete with pathogens for adhesion sites and nutrients within the gut. This competition can limit the colonization and growth of pathogenic bacteria.
   Furthermore, probiotics can produce antimicrobial compounds, such as organic acids, bacteriocins, and hydrogen peroxide, that exert inhibitory effects on pathogenic bacteria. These compounds disrupt the cellular structures and metabolic processes of pathogens, leading to growth inhibition. Probiotics may also modulate the host immune response, enhancing the body's defense mechanisms against foodborne pathogens. As a result, incorporating probiotics into food products or dietary supplements holds promise as a preventive measure against pathogen-related illnesses (Hossain et al., 2017 ; Rodriguez-Sanchez et al., 2021).
3. **Antagonistic Microorganisms:** Certain beneficial microorganisms, such as lactic acid bacteria and yeasts, exhibit antagonistic properties against foodborne pathogens. Lactic acid bacteria, for instance, can lower the pH of their environment through the production of organic acids, creating conditions unfavorable for pathogen growth. They also produce antimicrobial compounds, including bacteriocins, which directly inhibit the growth of pathogens.
   Yeasts, on the other hand, can compete with pathogens for nutrients and produce antifungal metabolites that impede the growth of spoilage microorganisms. These antagonistic microorganisms are commonly employed in food fermentation processes, contributing to the preservation and safety of fermented foods (Gao et al., 2019).
4. **Enzymes and Metabolites:** Enzymes and metabolites produced by microorganisms have garnered interest for their potential antimicrobial properties. Enzymes such as lysozyme and proteases can target the cell

walls and proteins of pathogens, disrupting their integrity. Metabolites like hydrogen peroxide and antimicrobial peptides can interfere with microbial growth and survival. The application of these enzymatic and metabolic products, either directly or through engineered formulations, offers a unique approach to controlling foodborne pathogens (Fidan et al., 2022).

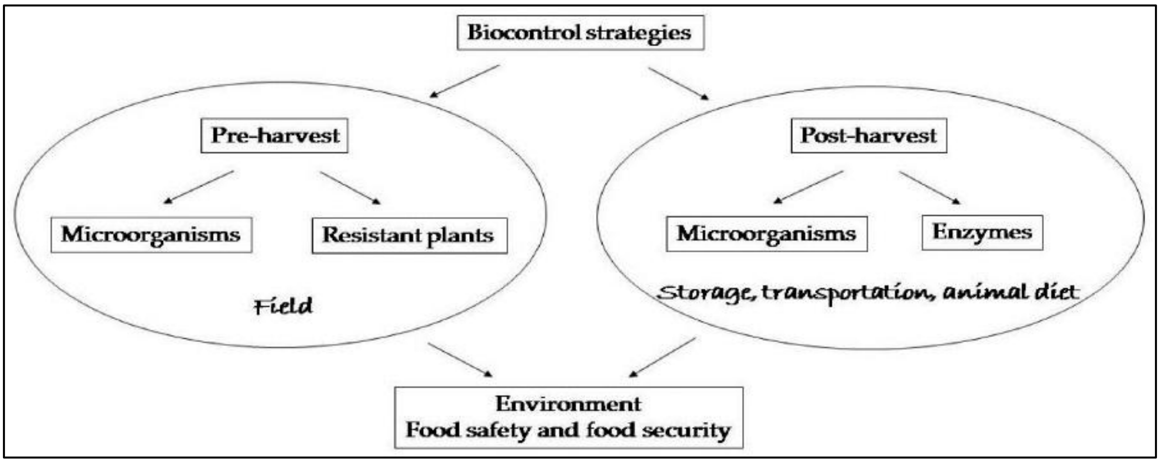

Figure 1: A schematic presentation of the biological strategies

Mechanisms of Action

Biological control agents employ a range of mechanisms to exert inhibitory effects on foodborne pathogens. These mechanisms relies on the natural interactions between microorganisms to mitigate the growth and survival of pathogens.

1. **Competition for Nutrients:** One of the fundamental mechanisms utilized by biological control agents is competition for nutrients. Beneficial microorganisms can outcompete foodborne pathogens for essential nutrients, limiting the resources required for pathogen growth. This competitive exclusion hinders the ability of pathogens to establish themselves and proliferate within the microbial community (McIntyre et al., 2012).
2. **Production of Antimicrobial Compounds:** Many biological control agents possess the capability to synthesize antimicrobial compounds that inhibit the growth of foodborne pathogens. For instance, bacteriocins, small antimicrobial peptides produced by certain bacteria, are effective weapons against pathogens. Bacteriocins disrupt the integrity of the target cell's membrane, leading to cell death. Additionally, organic acids produced by microorganisms can lower the pH of the environment, creating conditions unfavourable for pathogen survival (Galvez et al., 2008).
3. **Biofilm Disruption:** Foodborne pathogens often form biofilms on various surfaces, which provide protection from environmental stressors and antimicrobial agents. Biological control agents can disrupt these biofilms, rendering pathogens more vulnerable. Enzymes produced by certain microorganisms degrade the extracellular matrix of biofilms, destabilizing their structure and enhancing the susceptibility of pathogens to antimicrobial treatments (Gray et al., 2018).
4. **Quorum Sensing Interference:** Quorum sensing is a cell-to-cell communication mechanism used by bacteria to coordinate group behaviours. Some biological control agents can interfere with quorum sensing systems of foodborne pathogens. This interference disrupts the communication networks that facilitate pathogen virulence and biofilm formation. By modulating quorum sensing, biological control agents can attenuate the pathogenic potential of foodborne pathogens (Romero et al., 2012).

Applications in Food Production

Biological control methods offer diverse applications throughout various stages of food production (figure 1).

1. **Pre-harvest Interventions:** Biological control agents have found valuable applications in pre-harvest interventions within agricultural settings to mitigate the risk of pathogen contamination in crops. This approach involves the introduction of beneficial microorganisms or their products into the growing environment to compete with or antagonize potential pathogens. By establishing a balanced microbial community on plants or in the soil, the growth and survival of foodborne pathogens can be suppressed, reducing the likelihood of crop contamination.

   For example, Hagens and Loessner (2010) emphasize the use of bacteriophages, which are viruses that specifically target bacteria, as a precise and natural way to control foodborne pathogens. They also proposed introducing bacteriophages into the growing environment before harvest to effectively lower the risk of pathogen contamination in crops. By infecting and dismantling harmful bacterial pathogens, bacteriophages play a crucial role in improving the overall safety of fresh and ready-to-eat food products.

2. **Post-harvest Interventions:** In post-harvest interventions, biological control agents contribute to maintaining food quality and safety during food processing, storage, and distribution. After harvesting, crops are vulnerable to contamination by foodborne pathogens during handling, transportation, and storage. By applying biological control agents or their derived products, the growth of pathogens can be suppressed, thereby extending the shelf life of fresh produce and minimizing the potential for disease transmission.

   In a study by Berrios-Rodriguez et al. (2020), post-harvest disease control was explored using biocontrol agents. The research highlighted the potential of non-pathogenic Pseudomonas fluorescens in combination with other interventions, such as gamma radiation and sanitizers, to reduce Listeria monocytogenes survival on post-harvest carrot and tomato. This underscores the promising role of biocontrol methods in enhancing the safety of harvested produce.

3. **Packaging Innovations:** Emerging trends in food packaging technology have led to innovative approaches involving the incorporation of biological control agents. Bioactive packaging materials are designed to release or activate antimicrobial compounds from the biological control agents, creating a controlled and continuous release of inhibitory substances. These agents can maintain low pathogen levels on the food surface and within the package, reducing the risk of contamination and spoilage.

   Biological control-based packaging materials may include edible films, coatings, or sachets that contain antimicrobial peptides, enzymes, or probiotic bacteria. These materials not only provide protection against pathogens but also offer the potential to enhance the sensory and nutritional quality of packaged foods. Such packaging innovations align with consumer demands for natural and sustainable food preservation methods (Suppakul et al., 2003).

Conclusion

The application of biological control agents presents a promising method for enhancing food safety and quality. This eco-friendly approach, rooted in natural ecological interactions, provides specificity in targeting pathogens while preserving beneficial microorganisms. Bacteriophages, probiotics, antagonistic microorganisms, and enzymatic agents demonstrate diverse mechanisms to inhibit pathogen growth. Implementing these methods across food production stages, From pre-harvest interventions that establish a balanced microbial community to post-harvest measures that restrict pathogen growth. While chemical interventions raise concerns, biological control offers a precise and non-toxic pathogen management.

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