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Yeast-Based Biofungicides as Emerging Tools in Post-Harvest Disease Management

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Post-harvest losses caused by fungal pathogens pose a major challenge to global fruit and vegetable supply chains, leading to significant economic losses and food insecurity. Conventional chemical fungicides have been widely used to control post-harvest diseases; however, their repeated application has resulted in fungicide resistance, environmental contamination, and growing concerns over chemical residues on produce. In this context, yeast-based biofungicides have emerged as promising, eco-friendly alternatives for sustainable post-harvest disease management. Yeasts exhibit strong antagonistic activity against a wide range of post-harvest pathogens through multiple mechanisms, including competition for nutrients and space, production of antifungal metabolites, secretion of lytic enzymes, induction of host defence responses, and biofilm formation. This review critically synthesizes recent advances in yeast-based biofungicides, emphasizing their mechanisms of action, formulation strategies, efficacy against major post-harvest pathogens, integration with omics technologies, and future prospects for commercial application. The review highlights yeast biofungicides as versatile and residue-free tools that align with the goals of sustainable and climate-resilient post-harvest disease management.

Keywords: Yeast biofungicides; post-harvest diseases; biological control; antagonistic yeasts; sustainable agriculture; residue-free management; omics technologies

Introduction

Post-harvest diseases caused by fungal pathogens represent one of the most significant constraints to the quality, shelf life, and marketability of fruits and vegetables worldwide. It is estimated that 20–30% of harvested produce is lost annually due to post-harvest decay, with losses reaching even higher levels in developing countries owing to inadequate storage and handling practices. Major post-harvest pathogens such as *Botrytis cinerea*, *Penicillium expansum*, *Colletotrichum* spp., and *Alternaria* spp. infect produce during harvesting, transportation, and storage, resulting in rapid deterioration and economic loss.

Chemical fungicides have traditionally been the primary means of controlling post-harvest diseases. While effective in the short term, their extensive use has led to several critical concerns, including the development of fungicide-resistant pathogen strains, accumulation of chemical residues on produce, negative impacts on non-target organisms, and stricter regulatory restrictions. Consumer demand for safe, residue-free food has further intensified the need for alternative disease management strategies.

Biological control using antagonistic microorganisms has emerged as a viable and sustainable alternative to chemical fungicides. Among biological control agents, yeasts have gained considerable attention due to their natural occurrence on fruit surfaces, rapid growth, genetic stability, and strong antagonistic activity against post-harvest pathogens. Yeast-based biofungicides are particularly attractive because they rarely produce mycotoxins, can survive under harsh storage conditions, and are generally regarded as safe (GRAS).

Recent advances in microbial ecology, genomics, metabolomics, and formulation technologies have further strengthened the potential of yeast-based biofungicides in post-harvest disease management. This review aims to provide a comprehensive synthesis of current research on yeast-based biofungicides, focusing on their mechanisms of action, formulation approaches, agronomic relevance, limitations, and future research directions.

Mechanisms of Action of Yeast Biofungicides

Yeast antagonists suppress post-harvest pathogens through multiple, often synergistic mechanisms, which reduces the likelihood of resistance development.

Competition for Nutrients and Space: One of the primary mechanisms by which yeasts suppress fungal pathogens is competition for nutrients and colonization sites on fruit surfaces and wounds. Rapid colonization by yeasts deprives pathogens of essential nutrients, particularly sugars and amino acids, thereby inhibiting spore germination and mycelial growth.

Production of Antifungal Metabolites: Several yeast species produce volatile and non-volatile antifungal compounds, including organic acids, alcohols, and killer toxins. These metabolites disrupt pathogen cell membranes, inhibit enzymatic activity, and interfere with fungal metabolism.

Secretion of Lytic Enzymes: Yeasts can produce hydrolytic enzymes such as chitinases, β-1,3-glucanases, and proteases that degrade fungal cell walls. This enzymatic activity weakens pathogen structures and enhances pathogen suppression.

Induction of Host Defense Responses: Some antagonistic yeasts stimulate host defense mechanisms by inducing systemic resistance in fruits. This includes activation of defense-related enzymes, accumulation of phenolic compounds, and enhancement of antioxidant systems.

Biofilm Formation and Quorum Sensing: Yeasts can form biofilms on fruit surfaces, providing a physical barrier against pathogen invasion. Quorum sensing further regulates population density and enhances collective antagonistic behavior.

Major Yeast Species Used as Biofungicides

Several yeast genera have demonstrated strong antagonistic activity against post-harvest pathogens:

- *Candida* spp.
- *Pichia* spp.
- *Metschnikowia pulcherrima*
- *Aureobasidium pullulans*
- *Rhodotorula* spp.
- *Cryptococcus* spp.
- *Saccharomyces cerevisiae*

Commercial products such as Aspire® (*Candida oleophila*) and BoniProtect® (*Aureobasidium pullulans*) have validated the practical feasibility of yeast-based biofungicides.

Formulation and Delivery of Yeast Biofungicides

Successful commercialization of yeast biofungicides depends on effective formulation strategies that ensure microbial survival, shelf life, and field performance.

Solid and Liquid Formulations: Yeasts are formulated as wettable powders, granules, or liquid suspensions using carriers such as starch, talc, and alginate.

Encapsulation and Nano-Formulations: Encapsulation techniques using polymers and nano-carriers protect yeast cells from environmental stress and enhance their persistence on fruit surfaces.

Integration with Natural Additives: Combination of yeasts with natural compounds such as chitosan, essential oils, and calcium salts has shown synergistic effects in disease suppression.

Role of Omics Technologies in Yeast Biofungicide Development

Advances in genomics, transcriptomics, proteomics, and metabolomics have significantly contributed to the understanding and improvement of yeast biofungicides.

- **Genomics** aids in identification of genes involved in antagonism and stress tolerance.
- **Transcriptomics** reveals gene expression changes during pathogen interaction.
- **Metabolomics** identifies bioactive antifungal compounds.
- **Proteomics** elucidates enzyme systems involved in pathogen suppression.

These tools facilitate the selection and optimization of superior yeast strains for post-harvest disease management.

Agronomic and Environmental Benefits

Yeast-based biofungicides offer several advantages over chemical fungicides:

- Residue-free disease control
- Reduced risk of resistance development
- Compatibility with organic farming systems
- Improved shelf life and fruit quality
- Environmentally safe and biodegradable

Limitations and Challenges

Despite their promise, yeast biofungicides face several challenges, including:

- Variable efficacy under commercial storage conditions
- Limited shelf life compared to chemical fungicides
- Sensitivity to temperature and humidity extremes
- Higher production and formulation costs

Future Prospects

Future research should focus on:

- Development of multi-strain yeast consortia
- Integration with precision post-harvest technologies
- Advanced formulations for improved shelf life
- Large-scale field validation and cost–benefit analysis

Yeast biofungicides are expected to play a key role in sustainable post-harvest disease management under climate-smart agriculture frameworks.

Conclusion

Yeast-based biofungicides represent an emerging and sustainable alternative to chemical fungicides for post-harvest disease management. Their multiple mechanisms of action, environmental safety, and compatibility with residue-free food production make them highly suitable for modern agriculture. While challenges remain in formulation and commercialization, advances in omics technologies and bioformulation strategies are likely to accelerate their adoption. Overall, yeast biofungicides hold strong potential as core components of integrated post-harvest disease management systems

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