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Combating *rhizopus* soft rot in papaya fruit: pathology, post-harvest impact, and control strategies: A review

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Abstract
Papaya (*Carica papaya*) is a tropical fruit valued for its nutritional benefits and economic importance, yet it is highly vulnerable to post-harvest decay, especially soft rot caused by *Rhizopus stolonifer*. This review explores the biology of *R. stolonifer*, the pathology of soft rot in papaya, and its detrimental effects on post-harvest quality and marketability. Emphasis is placed on innovative, eco-friendly strategies for managing this disease, including biological control agents, edible coatings plant-based antimicrobials modified atmosphere storage, cold plasma, UV-C irradiation, nanotechnology and smart packaging. These approaches promise to reduce post-harvest losses while ensuring food safety and sustainability.

Keywords: *Rhizopus stolonifer*, post-harvest, soft rot, food safety

Introduction
Papaya (*Carica papaya*), commonly referred to as pawpaw in some regions, is a fast-growing tropical fruit-bearing plant belonging to the *Caricaceae* family. Native to Central America and southern Mexico, papaya has become a globally cultivated crop, especially in tropical and subtropical regions such as India, the Philippines, Thailand, and parts of Africa. It is prized not only for its sweet, succulent flesh and aromatic flavour but also for its impressive nutritional profile Rich in essential vitamins, minerals, and bioactive compounds, papaya serves as a valuable dietary component in many cultures.
The fruit is particularly known for its high content of vitamin C, vitamin A (in the form of beta-carotene), folate, potassium, and dietary fibre. Additionally, it contains the proteolytic enzyme papain [1] which aids in protein digestion and has various industrial and medicinal applications. Papaya's versatility extends beyond its consumption as fresh fruit; it is used in juices, smoothies, salads, and culinary preparations, while the unripe green fruit is often incorporated into savoury dishes. Furthermore, papaya seeds and leaves have been traditionally employed in folk medicine for their purported health benefits, including antimicrobial, anti-inflammatory, and antiparasitic properties.
Despite its widespread cultivation and demand, papaya is highly perishable and susceptible to post-harvest diseases, particularly under warm and humid conditions. These diseases contribute significantly to economic losses during storage, transportation, and marketing. Among the various pathogens affecting papaya, *Rhizopus stolonifer*—a fast-growing filamentous fungus commonly known as black bread mold—poses a substantial. This saprophytic organism becomes pathogenic under favourable conditions, causing soft rot [2], a rapid and devastating post-harvest disease that severely compromises fruit quality [3].
The impact of soft rot extends beyond physical spoilage, affecting the fruit's market value, nutritional content, and consumer acceptability. Given the increasing demand for high-quality, safe, and residue-free produce, there is a pressing need to explore innovative, sustainable strategies to mitigate the impact of post-harvest diseases. This review delves into the etiology and pathology of soft rot in papaya, evaluates its implications on post-harvest quality, and highlights recent advances in eco-friendly disease management approaches aimed at reducing spoilage and ensuring food safety.

Types of Papaya Fruit Rots
Papaya is vulnerable to several types of fruit rots, each caused by different pathogenic organisms and exhibiting unique symptoms (Table 1). Among the most widespread is anthracnose fruit rot, caused by the fungus *Colletotrichum gloeosporioides*. This disease typically begins as small, water-soaked lesions on the surface of the fruit, which progressively expand into sunken, dark brown to black spots with concentric rings. Under humid conditions, the lesions exude pinkish-orange spore masses, which facilitate rapid spread, especially during post-harvest handling and storage.

Table 1: Papaya fruit rot types

Type of Rot	Causal Agent	Symptoms	Favourable Conditions	Reference
Rhizopus Soft Rot	*Rhizopus stolonifer*	Water-soaked lesions, rapid softening, white cottony mycelium with black sporangia	High humidity, warm temperatures, physical damage to fruit	[3]
Anthracnose	*Colletotrichum gloeosporioides*	Sunken, black lesions with orange spore masses	High humidity, postharvest infection	[4]
Phytophthora Rot	*Phytophthora palmivora*	Dark, water-soaked lesions, rapid fruit decay	Wet conditions, soil contact	[5]
Alternaria Rot	*Alternaria alternata*	Blackish-brown lesions, often with concentric rings	Prolonged wet conditions, senescent fruit	[6]
Stem End Rot	*Lasiodiplodia theobromae, Phomopsis spp., Alternaria spp.*	Dark brown to black decay at the stem end, gradually spreading to the rest of the fruit	High humidity, poor postharvest handling	[8]

Collectively, these various fruit rots severely impact the post-harvest quality and marketability of papaya, necessitating effective disease identification and management strategies to mitigate losses [8].

1. Soft Rot / *Rhizopus* Rot

Rhizopus rot, or soft rot, is caused by *Rhizopus stolonifer*, and is characterized by rapid and extensive tissue maceration. This disease typically begins at wounds or bruised areas on the fruit's surface, as the fungus cannot penetrate intact skin. Once inside, it rapidly colonizes the soft tissue, leading to water-soaked lesions that expand quickly and cause the fruit to become mushy and collapse. A distinctive feature of *Rhizopus* rot is the development of fluffy white mycelium on the surface of the infected fruit, which later turns black due to the formation of sporangia containing numerous sporangiospores [5, 9]. These spores are readily dispersed through air currents, particularly in storage facilities with inadequate ventilation or poor hygiene. Under optimal conditions, such as temperatures between 20–30°C and high humidity, the fungus can complete its life cycle within a few days, leading to widespread infection of adjacent fruits. Infected fruits emit a sour, unpleasant odour as the tissue decomposes, further reducing their marketability and raising concerns over food safety [10, 11].

Impact on Post-Harvest Quality

Soft rot caused by *Rhizopus stolonifer* has a profound impact on the post-harvest quality of papaya fruits. The disease leads to the development of large, soft, water-soaked lesions on the fruit surface, resulting in an unattractive and moldy appearance that renders the fruit unmarketable. As the fungus invades the fruit tissue, enzymatic breakdown causes maceration, leading to a slimy, mushy consistency and a significant loss of the characteristic sweet flavour of ripe papaya. Infected fruits also suffer a marked reduction in nutritional value, including the depletion of essential vitamins such as vitamin C [7, 8], along with antioxidants and other beneficial phytochemicals.

Additionally, the rapid spread of soft rot significantly shortens the shelf life of papaya, contributing to increased spoilage during storage, transportation, and marketing. This not only results in direct economic losses from unsalable produce but also incurs additional costs associated with sorting and disposal of spoiled fruits. The presence of fungal decay and potential microbial contamination poses food safety concerns [14, 15], particularly for consumers with compromised immune systems. Overall, the effects of soft rot extend beyond physical deterioration, impacting the economic viability and consumer trust in papaya supply chains.

Innovative Control Measures

Innovative strategies for managing soft rot in papaya emphasize sustainable and environmentally friendly approaches (Table 2). Biological control agents, such as beneficial microorganisms including *Trichoderma* spp., *Bacillus subtilis*, and *Pseudomonas fluorescens*, have been shown to effectively suppress *Rhizopus stolonifer* through mechanisms like antibiosis and nutrient competition. These microorganisms can be applied in various forms, including fruit dips and sprays, to provide natural protection against fungal invasion.

Table 2: Control measures of papaya fruit rot

Control Measure	Method	Effectiveness	Reference
Biocontrol Agents	Use of *Trichoderma* spp., *Bacillus subtilis*	Suppresses fungal growth, eco-friendly	[16, 17, 18]
Essential Oils	Application of neem, clove, or thyme oils	Antifungal properties, reduces postharvest rot	[5]
UV-C Treatment	Exposure to short-wavelength UV-C light	Delays fungal growth, extends shelf life	[17, 18, 19]
Edible Coatings	Aloevera gel, chitosan-based coatings	Forms protective layer, inhibits fungal invasion	[5, 6]
Modified Atmosphere Packaging	Reduced oxygen, increased CO_2	Slows down fungal metabolism, preserves freshness	[8, 11]
Silicon-based Treatments	Foliar application of silicon compounds	Enhances plant resistance, reduces infection risk	[9, 20]

Smart packaging and sensor technology allow for real-time monitoring of fruit spoilage and microbial contamination. These systems often utilize colour changes or electronic signals to indicate spoilage, facilitating early detection and removal of infected fruits. Some packaging materials also integrate natural antimicrobial agents to directly inhibit fungal growth within the storage environment.

Conclusion

Rhizopus soft rot poses a significant threat to papaya production, leading to considerable economic losses and reduced fruit quality. This study highlights the critical factors contributing to the disease, including environmental conditions, pathogen virulence, and post-harvest handling practices. By implementing effective control measures such as improved sanitation, proper storage conditions, and the use of antifungal treatments, the incidence of *Rhizopus* soft rot can be minimized [7]. Additionally, integrating biological control methods and exploring resistant papaya varieties could offer sustainable long-term solutions [15]. Future research should focus on developing innovative strategies that balance disease management [17] with environmental sustainability. By adopting a holistic approach, farmers and stakeholders can enhance papaya shelf life, reduce losses, and ensure a more stable supply chain for consumers worldwide.

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