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Advanced Strategies for Mitigating Postharvest Deterioration in Soft Fruits

Mohsin Raza[1], Muhammad Asad Saleem[2], Mudassar Naseer[2], Amjad Farooq[3], Shakir Ali[4], Abdul Hafi[5], Hafiz Usama Noor[6], Muhammad Hamdan Rashid[6], Iman Shafquat[1]

[1]Institute of Horticultural Sciences, University of Agriculture, Faisalabad, Punjab, Pakistan.
[2]Horticultural Research Station, Sahiwal, Punjab, Pakistan.
[3]Department of Environmental Sciences, COMSATS University Islamabad, Vehari Campus, Punjab, Pakistan.
[4]School of Landscape Architecture, Beijing Forestry University, China.
[5]Nutrien Ag Solutions, Saskatoon, Saskatchewan, Canada.
[6]Post Harvest Research Centre, Ayub Agricultural Research Institute, Faisalabad, Punjab, Pakistan.

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Corresponding Author: Mohsin Raza
Institute of Horticultural Sciences, University of Agriculture, Faisalabad, Punjab, Pakistan.
Email: mr88355555@gmail.com

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ABSTRACT

Preventing disease incidence in soft fruit post-harvest presents a substantial challenge. This study examines traditional methods and emerging technologies employed to address this issue. Conventional approaches typically regulate fruit ripening and pathogen proliferation through low-temperature storage and modified atmosphere techniques. Various methodologies such as irradiation, brief heat treatments, and chemical applications (e.g., calcium, 1-Methylcyclopropene, nitric oxide). Physical methods like heat treatments and irradiation promise to extend soft fruit's shelf-life. Biological control and treatments that stimulate the fruit's innate responses exhibit potential, particularly considering fungicide restrictions. Before commercial implementation, it is crucial to comprehend the diverse facets of these techniques. Progress in plant metabolic engineering may diminish fruit susceptibility to diseases. Swift cooling and low-temperature storage (at 0°C with 90-95% relative humidity) are indispensable for preserving soft fruit and necessitate integrated pre-harvest and post-harvest strategies. While emerging technologies may complement low-temperature storage and modified atmospheres, evaluating their feasibility and constraints on a commercial scale is imperative. Testing novel techniques under low-temperature conditions is essential for exploring alternatives that enhance existing methods. Further research is warranted to elucidate fruit-pathogen interactions, encompassing factors of pathogen virulence and the regulation of natural fruit-defense strategies. This information would be invaluable for the identification of candidate genes for breeding, the development of biotechnological approaches, and the establishment of consistent and efficacious methods rooted in the activation of the fruit's innate defense system.

INTRODUCTION

Soft fruits are essential components in many delicacies, including jellies, yogurt, frozen desserts sauces, and preserves (Thakur et al., 2022). They can be consumed fresh. Typically encompassing raspberries, blackberries, blueberries, and strawberries along with their hybrids, this category holds practical significance despite variations in taxonomy and edible organ composition among species. Noteworthy characteristics of these delectable fleshy structures include a rapid softening rate and the presence of anthocyanins, imparting their distinctive blue or red hue. Soft fruits are often deemed non-climacteric exhibiting minimal ethylene production (0.1–1µl $C2H4$/kg/h at 20°C) and low sensitivity. Despite their limited postharvest longevity, they hold significant economic value (Hewett). Their accelerated softening and susceptibility to postharvest pathogens underscore their perishability (Petrasch, 2020). This article provides an overview of both traditional and innovative methods to mitigate soft fruit spoilage.

Spoilage in Soft Fruits

A notable constraint on the postharvest longevity of soft fruit is the widespread existence of diseases. *Mucor mucedo*, *Colletotrichum acutatum*, *Rhizopus stolonifer*, and *Botrytis cinerea* are the pathogens responsible for initiating decay (Singh and Singh, 2021). During postharvest storage and retail, *Rhizopus stolonifer* and *B. cinerea* are regularly linked with pathogenicity (Zhang et al., 2020).

Gray Mold Rot

More than 200 plant species fall victim to the polyphagous pathogen *B. cinerea*, potentially causing severe post-harvest storage complications and resulting in annual losses totaling billions of dollars. Optimal conditions for infection encompass inadequate ventilation, and heightened relative humidity rates, especially prevalent during spring and fall, conducive to pathogen proliferation (Head, 2022). Although ripe fruit typically displays severe infection signs and tissue disintegration, the infection often initiates in blossoms and may remain dormant. Typically, decaying areas manifest at the fruit's base due to contaminated petals or stamens adhering to the calyx or other regions (Tane, 2022), further facilitated by existing sores and lesions caused by insects and other diseases. Initially appearing as small yellowish patches, symptoms progress to form brown, uneven, squishy areas eventually enveloped by white mycelia and grey spores, potentially spreading throughout the entire fruit (Parthasarathy et al., 2024). The proliferation of conidia from affected fruit accelerates disease transmission (Ji et al., 2024).

Rhizopus Rot

Rhizopus stolonifer spores propagate rapidly due to their frequent airborne dispersion (Walther et al., 2020). The fungus usually infects mature fruit through wounds. Infected fruit forms squalid spots, shifting to a pale brown shade, then merging and discharging contents. Subsequently, a white mycelium, characterized by lengthy sporangiophores terminating in black sporangia, may encase the fruit (Massee, 1891). Despite its widespread dispersion, Rhizopus-induced rotting has diminished in occurrence because pathogen progression and sporulation are suppressed when stored below 5°C (Sun et al., 2017).

Strategies to Control Spoilage

To mitigate soft fruit spoilage, various strategies can be implemented.

Inoculum Reduction

Minimizing the quantity of inoculum remains the primary method for mitigating soft fruit rot. Consequently, optimal control of postharvest infections occurs primarily in the field. Preharvest disease management is paramount, given strawberries' exemption from postharvest fungicidal treatment (Weber and Petridis, 2023). Effectively managing Botrytis hinges significantly on cultural practices. These steps involve using disease-resistant crops, removing infected fruit and other parts, and controlling the amount of moisture on fruit surfaces. Given the potential for excessive canopy humidity, drip-tape irrigation may be preferable over overhead sprinkler systems. Mitigating Botrytis prevalence further entails avoiding dense plantings, judicious nitrogen application, and mulching to prevent soil contact(Chen et al., 2023). Fungicidal sprays play a pivotal role in integrated control programs aimed at disease containment and rot prevention (Palmieri et al., 2022). Unlike other pathogens, Botrytis can develop under favorable conditions despite effective fungicide regimens. Benzimidazole fungicides such as benomyl and thiophanate methyl have demonstrated efficacy against Botrytis (Avenot et al., 2020). More recently, the introduction of dicarboximide fungicides like vinclozolin and iprodione has enhanced pathogen control (Sun et al., 2023). However, like benzimidazole fungicides, resistance has emerged against these compounds. Weekly applications of Captain, one of the few fungicides suitable for near-harvest use, effectively control Botrytis fruit rot in strawberries(Murray et al., 2012).

Fruit Harvesting and Handling

In every postharvest disease management program, harvesting practices play a crucial role. Wounds serve as entry points for most postharvest infections into the host tissues (Droby et al., 2022). Therefore, every procedure should aim to minimize bodily harm, bruising, and wounds. Early harvesting reduces susceptibility to infections due to delayed sugar buildup in ripening stages; however, it compromises flavor and perfume (Droby et al., 2022). Harvesting should coincide with the absence of free water on the fruit's surface, as moist fruit is more prone to disease assault. Harvesting at moderate temperatures reduces residual field heat, which lessens the load during cooling operations (Xu et al., 2020). Utilizing only sanitized and decontaminated containers with non-abrasive surfaces is recommended. Affected berries may harbor numerous fungal spores or exhibit fragility and leakage upon harvest, necessitating pickers to have containers for leftover fruit to mitigate infection risks. Minimizing fruit damage entails reducing the interval between harvest and transportation and ensuring adequate roads and vehicles (Al-Dairi et al., 2022). Removing diseased fruit and tissue remnants from packing houses is another protective measure as pathogens often accompany fruit during shipment. To maintain fruit quality, diligent sanitation is imperative, considering the potential pollution of air, water, and equipment over time (Lebelo et al., 2021).

Cooling and Storage Condition

It is widely acknowledged that controlling the temperature of fruit is pivotal for preserving its quality, particularly concerning soft fruit (Lufu et al., 2020). Room chilling has long been utilized to cool agricultural produce. Although this method usually maintains low temperatures after chilling, it often struggles to rapidly remove field heat, crucial for preserving highly perishable crops' quality. Forced-air cooling can adequately chill soft fruit, significantly reducing metabolic activity, thereby delaying softening, and diminishing susceptibility to rot (Mahajan and Kapoor, 2021). Depending on airflow velocity, Cooling rates may be four to ten times faster than at ambient temperature. Alternative methods like vacuuming or hydro-cooling may inflict more harm and increase water loss, thereby predisposing the fruit to disease. Within a cooling chamber, produce bundles are pressured to cool as higher air pressure on one side forces cold air through the packaging, extracting the fruit's heat. Properly filling and stacking containers are vital to minimize gaps and holes that disrupt airflow through the packages. Containers must ensure adequate ventilation by providing sufficient open space on the sides and bottom, with 5-8% of the peripheral surface and 3-5% of the bottom accessible. The ideal storage temperature for raspberries, blackberries, blueberries, and strawberries is 0ºC (Huynh, 2021). Maintaining humidity above 100%, alongside regulating air temperature and flow, is crucial as produces wilts, shrinks, and loses quality due to water loss (Shoji et al., 2022). Delayed chilling adversely affects soft fruit quality, leading to 50% more water loss and shriveling when chilling commences six hours later than planned. Cooling delays also result in increased firmness loss and reduced levels of acids, soluble solids, and ascorbic acid (Bhardwaj et al., 2022). The optimal storage temperature for chilled berries ranges from 0 to 1ºC(Sabir et al., 2010). Blueberries remain viable for approximately two weeks post-harvest, whereas strawberries persist for seven to ten days. Conversely, raspberries and blackberries sustain viability for merely three to five days. These fruits exhibit high susceptibility to water loss, leading to rapid deterioration if the relative humidity drops below 85–95% (Huynh, 2021).

Controlled and Modified Atmosphere

To uphold the freshness of perishable foods and extend their shelf life, modified/controlled atmospheres (MA/CA) are employed alongside temperature regulation. Modified or controlled atmospheres may be employed to ensure the freshness of perishable foods and extend their shelf life(Kargwal et al., 2020).

O2 Modification

Storage in 60-100% oxygen can decrease decay but adversely affect the fruit's taste and aroma. lowering oxygen levels to 1% at 5°C can inhibit fruit softening and decay while maintaining other quality traits (Pott et al., 2020).

CO2 Modification

By interfering with fungal disease metabolic processes, high-CO2 treatments mitigate postharvest rots caused by these pathogens (Sharma, 2020). Additionally, CO2 may hinder fruit ripening. The CO2 concentration needed to inhibit mycelium development varies depending on the fungus type. Maintaining the lowest feasible temperature and CO2 concentration tolerable by the plant product markedly suppressed fungus growth and spore germination in *B. cinerea* and various fungal pathogens (Barkai-Golan, 1990). Soft fruits, relatively resistant to high CO2 partial pressures, are stored in CO2-enriched atmospheres (10–20% in air) to extend postharvest life (Horvitz, 2017). CO2-treated strawberry fruit exhibits reduced respiration, delayed softening, or even increased firmness. Most cultivars display CO2-induced hardness increases, influenced by berry maturity, with pH variations in the apoplast hypothesized to be the mechanism behind CO2-induced firmness augmentation in strawberries. These pH shifts may promote soluble pectin precipitation, strengthening cell cross-linking in strawberry fruit (Belay, 2017). While controlled atmosphere (CA) and modified atmosphere (MA) techniques offer numerous benefits, exposure to CO2 concentrations exceeding 20% or very low O2 levels can lead to adverse effects, including increased acetaldehyde, ethanol, and ethyl acetate levels. Elevated CO2 levels can cause external strawberry fruit color to shift from red to red-purple while reducing redness in internal tissues (Rezaiyan Attar et al., 2023).

Carbon Monoxide

Strawberries have exhibited fungistatic effects of carbon monoxide while maintaining quality. A model was developed to predict how different temperature and air variables would influence fruit deterioration caused by *B. cinerea*. The suggested model accounted for 83% of the experimental data across various fruit batches. Although such a method holds promise for adjusting packaging and transit conditions to meet specific product requirements, the fruit-pathogen interaction demands a more nuanced approach than the current model provides. Examining how environmental factors affect fruit degradation and quality while accounting for customer acceptance, could be highly advantageous, mirroring the growth of models.

Irradiation

Radiation has been employed to control infections or insects and delay processes associated with ripening (Kumari et al., 2017). The soft fruit has been utilized to assess different types of radiation.

Ionizing radiation

Insects and microbiological pests have been sterilized or killed through ionizing radiation. Raspberries and boysenberries can withstand doses of up to approximately 1 kg, whereas depending on the variety, strawberries may tolerate doses ranging from 2 to 4 kg (Stoner et al., 2008). Radiation treatment for strawberries has been employed, with varying degrees of effectiveness, to inhibit deterioration. However, berries often become too softened due to the doses necessary for effective decay management (Azam et al., 2019).

Ultraviolet Irradiation

Applying 0.5–4.5 kJ/m2 of ultraviolet-C (UV-C) light before storage has been utilized to prevent storage rots in strawberries (Sánchez et al., 2021). Pre-refrigeration treatments involving 9.2 kJ/m2 of UV-C radiation were found beneficial for boy sunberries. The method's efficacy may be linked, at least partially, to the germicidal properties of UV-C radiation. UV-C treatment (4.6 kJ/m2) hindered the germination of B. cinerea but had no impact on Rhizopus conidia (Vicente et al., 2005). Nonetheless, the germination of spores can be slowed in both fungi by combining treating heat with UV-C, enhancing spoilage prevention in strawberries. Following UV-C treatment, a study observed a reduction in decay induced by B. cinerea spores in strawberries, suggesting potential activation of fruit-defensive mechanisms, akin to observations with other fruits. UV-C irradiation heightened the activity of phenylalanine ammonia-lyase, an enzyme potentially pivotal in phenolic compound synthesis, many of which possess antifungal properties, bolstering disease resistance in UV-C-treated fruit (Ramalingam et al., 2024). UV-C treatment has demonstrated efficacy in reducing strawberry fruit softening, possibly by limiting cell wall breakdown, thereby impeding fungal pathogen tissue colonization(Montemayor, 2022).

Heat Treatment

Several studies demonstrate short postharvest heat treatments (HTs) offer benefits to vegetables and fruits (Fallik et al., 2020). Controlled strawberry degradation by applying moist air heating at 44ºC. Submerging in 45ºC water for 15 minutes reduces postharvest losses, maintains firmness, and enhances flavor. Application of Hot air at 45ºC for three hours resulted in delayed softening and decreased postharvest infections (Vicente et al., 2005). Combining HTs with standard refrigerated storage at 0ºC yielded positive outcomes. Executing this procedure with a low CO2 permeability layer enhances HT advantages, yielding a modified atmosphere (MA). Heat treatments typically induce delayed fruit ripening, leading to reduced vulnerability to diseases and softening. HT may also alter indirect defensive responses due to changes in the fruit ripening program. Reduced cell wall disintegration and elevated polyphenol oxidase activity in the fruit could inhibit tissue colonization (Bano et al., 2023).

Ozone Treatment

Ozone, renowned for its high reactivity and short half-life, is widely acknowledged as a safe disinfectant in food processing. It demonstrates potential for organic processing, such as post-harvest management. The mechanism of action of ozone is tied to its potent oxidative properties, allowing it to react with substances or hydroxyl free radicals generated during ozone decomposition, potentially assisting in pathogen control (Premjit et al., 2022). Moreover, ozone can impact fruit metabolism. In specific conditions, induced stress responses might enhance plant tolerance to subsequent stresses (Ma et al., 2020).

1-Methylcyclopropene

Recently, 1-methylcyclopropene (1-MCP) was incorporated into the plant product shelf-life and quality extenders database (López-García et al., 2022). This chemical is postulated to avidly bind ethylene receptors, thereby impeding ethylene binding, and initiating an inhibitory effect. Although most soft fruits are non-climacteric and do not undergo significant ripening acceleration in the presence of ethylene, exposure to this compound worsens strawberry deterioration during commercialization. 1-MCP mitigates softening and color alteration in strawberries (Langer et al., 2022). Nonetheless, diverse outcomes have been observed depending on 1-MCP concentrations and fruit ripening stages. Application of low 1-MCP concentrations has shown favorable effects, whereas elevated concentrations escalate the occurrence of illnesses (Liu et al., 2023). Utilizing 1-MCP treatment is unlikely to constitute a cost-effective approach for extending the shelf life of strawberries. Moreover, other soft fruits like boysenberries may exhibit less susceptibility to 1-MCP (Vicente et al., 2005). The significance of utilizing 1-MCP in soft fruits would be notably less compared to other fruits and vegetables.

Nitric Oxide

Plants naturally produce nitric oxide (NO), a compound scientifically demonstrated to modulate plant growth and development. NO's influence extends beyond whole plants; it can trigger beneficial reactions in fruits and vegetables during postharvest stages. Treatment with NO (5-10mL/L) for 2 hours before storage boosted strawberry postharvest longevity by 50% at 5ºC. The swift oxidation of NO to NO_2 in the presence of oxygen presents a substantial challenge to these interventions.

Chitosan

It has been extensively studied for its ability to prevent pathogenic fungi growth in soft fruit. Investigations have shown that dips in a chitosan solution are equally effective in safeguarding strawberry fruit from decay as fungicide treatments (Triunfo et al., 2023). Application of preharvest spray to mitigate early infections in the field and yield infection-free fruits. Although the precise mechanism of action of chitosan remains incompletely understood, its application may prompt plants to mount a more rapid response to pathogen attacks by enhancing chitinase and glucanase activity. Additionally, the induction of phytoalexins has been observed (Li et al., 2024).

Calcium Treatment

Calcium application has historically served to deter softening and decay in fruits and vegetables. Studies on strawberries have revealed that foliar $CaCl_2$ treatments can decelerate ripening and mold development. These treatments potentially impede cell wall breakdown, thereby reducing vulnerability to infections (Qadri et al., 2020). Strawberries treated with $CaCl_2$ have shown preservation of higher levels of ionically bound pectin, aiding in maintaining cell wall integrit (Wang et al., 2020). However, some studies indicate that $CaCl_2$ fails to offer protection against grey mold in strawberries. The efficacy of $CaCl_2$ sprays in enhancing strawberry quality and shelf life largely hinges on the rate of Ca^{2+} absorption by fruit tissues and the characteristics of the spray solution (Kahramanoglu, 2023). Limited calcium mobility in plants may explain variations in efficacy, particularly with foliar treatments, as fruit translocation might be minimal. Incorporating Tween 20 as an adjuvant could potentially enhance the efficacy of $CaCl_2$ sprays. Immersing strawberries in a 1% $CaCl_2$ solution has been demonstrated to mitigate postharvest deterioration and sustain firmness (Nguyen et al., 2020). Furthermore, calcium treatments have proven effective in preserving firmness in highbush blueberries and retarding ripening and decay in raspberries (Qu et al., 2022).

Biological Control

The exploration of alternatives to chemical-based postharvest disease control methods has recently expanded to develop approaches that are less hazardous to human health and the environment. Biological control garners attention as a promising fungicide application alternative (Riseh et al., 2022). Certain microorganisms with the capacity to regulate postharvest pathogens have been identified. In all experiments, strains of *Trichoderma viride* and *Gliocladium roseum* exhibited exceptional efficacy in suppressing B. cinerea, surpassing traditional captan sprays (Bera et al., 2022). Certain fungi, when applied to strawberry leaves harboring the pathogen, reduced the sporulation of B. cinerea. Yeasts demonstrate significant promise as biological control agents. During strawberry flower bloom, treatments with *Candida albidus* reduced gray mold on mature fruits post-harvest by 21-33% (Vicente et al., 2005). The yeast exhibited notably lower postharvest fruit rot incidence compared to fenhexamid. The yeast's effectiveness was enhanced when formulation components were incorporated into the cell solution. Trichoderma treatments substantially diminished B. cinerea levels in intentionally infected strawberries but were ineffective against latent infections (De Simone et al., 2021).

Other Methods

Several other alternative strategies have been studied for reducing soft fruit rotting.

Table 1
Some other methods and their effect on soft fruits' postharvest shelf life

Chemical	Application	Effect	Reference
Natural Volatiles	Postharvest Application of volatile compound at 10ºC storage temperature	maintain higher levels of sugars, organic acids, and oxygen radical absorbance capacity	(Wang, 2003)
Acetaldehyde	Treatment of acetaldehyde (AA) vapor (1500-6000 µl litre 1) for 4 hours	Suppresses pathogen development	(Rahman et al., 2023)
Ethanol	Application of ethanol spray one hour before harvest (50%v/v)	Decrease the incidence in strawberries of B. *cinerea*	(Wang et al., 2021)
Benzoic Acid	Application of 0.01M 2,5-dimethoxy benzoic acid	Reduction in decay in strawberry	(Azri et al., 2024)
Sodium Bicarbonate (antimicrobial agent food industry)	Application of 1% sodium bicarbonate sprays one hour before harvest to organically farmed strawberries.	Reduce the incidence of post-harvest diseases in strawberries	(Vicente et al., 2005)

CONCLUSION AND FUTURE PROSPECTIVE

Effective temperature management is indispensable for controlling the spoilage of soft fruit, notwithstanding the absence of a single strategy that guarantees 100% success. Biological control agents, brief heat treatments, UV-C irradiation, and calcium sprays have all proven effective in preventing fruit rot through scientific validation. However, many of these techniques lack comprehensive evaluation on a commercial scale, thus necessitating further study to ascertain their practicality under such conditions. The imperative testing of innovative approaches in low-temperature storage is essential for identifying enhancements to current systems. Biotechnology holds promise in elucidating fruit-pathogen interactions, discerning pathogenesis and defense-related genes, and facilitating breeding or genetic engineering to yield fungi-resistant fruit. Employing a combination of synchronized measures, commencing in the preharvest environment, and extending post-harvest, emerges as the optimal approach for preserving quality and mitigating soft fruit spoilage.

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