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A Comprehensive Review on Post Harvest Physiological Disorders in Citrus Fruit Crops (*Citrus* spp.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Post-harvest physiological disorders in citrus fruit crops (*Citrus* spp.) present significant challenges that impact both the economic and environmental aspects of global agriculture. This comprehensive review explored various dimensions of the subject, ranging from the description and classification of major disorders, such as chilling injury, rind staining, water loss, and mold, to the innovative detection and diagnostic techniques being employed in the industry. Through an extensive examination of prevention and management strategies, the review sheds light on pre-harvest factors, post-harvest treatments, and the role of modern technologies and agronomic practices in mitigating these disorders. It also delves into the economic losses and environmental consequences linked to different management approaches, underlining the need for sustainability and eco-friendly solutions. A particular focus is given to the emerging trends and technologies in the field, including nanotechnology, artificial intelligence, and natural treatments, all of which signal a shift towards a more integrated and sustainable management approach. By identifying current research gaps and the necessary future research direction, the review highlights opportunities for innovation and collaboration among growers, researchers, and policymakers. In addition, it emphasizes the broader implications of these disorders and their management on global trade, labor markets, and regulatory landscapes. This review serves as a valuable reference for stakeholders in the citrus industry, providing insights and guidance on best practices, technological advancements, and future perspectives. It represents an essential step towards aligning the citrus production with global sustainability goals and fostering a resilient industry capable of adapting to the ever-changing demands and challenges of the modern world.

Keywords: Citrus; post-harvest; physiological disorders; management; sustainability.

1. INTRODUCTION

Citrus belongs to the family Rutaceae and includes a variety of fruits such as oranges, lemons, grapefruits, and limes. Originating in Southeast Asia, the genus Citrus has been cultivated for thousands of years and is known for its rich nutritional content and unique flavor profile [1]. Over the centuries, the cultivation of citrus fruits has spread across the globe, adapting to different climates and growing conditions [2]. Citrus fruit crops play a significant role in the global agriculture. They are one of the most widely produced fruit crops, with major production areas found in the USA, Brazil, China, and India [3]. Citrus fruits are not only consumed fresh but are also processed into juices, jams, and other products, contributing to a multi-billion-dollar industry [4]. The citrus industry provides employment to millions of people and is an essential source of income for many farming communities [5]. The nutritional benefits, including a high vitamin C content, add to the value of citrus fruits in human diets worldwide [6]. Despite the economic and nutritional importance of citrus fruit crops, post-harvest physiological disorders remain a significant challenge [7]. These disorders can affect both the quality and market value of the produce, leading to substantial economic losses [8]. Common disorders include chilling injury, rind staining, water loss, and decay, often resulting from poor handling, storage, or transportation practices [9]. Addressing these disorders is crucial for maintaining the quality and safety of citrus products, as well as the profitability of the citrus industry. The purpose of this review is to provide a comprehensive overview of post-harvest physiological disorders in citrus fruit crops. By synthesizing existing research, this review aims to enhance understanding of the causes, detection, prevention, and management of these disorders [10]. The review will highlight the economic and environmental implications and offer insights into future research directions and technological innovations. The goal is to contribute valuable knowledge to growers, researchers, policymakers, and other stakeholders involved in the citrus industry [11]. This review focus on post-harvest physiological disorders in citrus fruit crops, including an examination of various species and cultivars within the Citrus genus. The methodology involves a systematic literature search across major databases, including PubMed, ScienceDirect, and Google Scholar, using keywords related to citrus, post-harvest, and physiological disorders [12]. Studies published in the last two decades will be prioritized to ensure relevance and currency. Both primary research articles and secondary reviews were considered, with an emphasis on experimental findings, technological advancements, and best practices in the field [13].

2. POST-HARVEST PHYSIOLOGY OF CITRUS FRUITS

The harvesting and post-harvest handling of citrus fruits play a vital role in maintaining quality and preventing physiological disorders. Harvesting at the correct stage of maturity ensures optimal flavor, texture, and nutritional content [14]. Proper tools and techniques are used to avoid mechanical injury, including careful hand picking or specialized machinery [15]. Once harvested, citrus fruits may be sorted, washed, and treated with post-harvest chemicals to prevent decay [16]. Post-harvest handling includes critical steps like pre-cooling, which helps in reducing field heat, and controlled atmosphere storage, which maintains optimal levels of humidity and gases to prolong shelf life [17]. Packaging and transportation methods are also vital in preserving quality and minimizing damage, and advances in these areas continue to influence post-harvest outcomes [18]. Understanding the physiological processes in citrus fruits after harvest provides insight into the potential disorders that may arise. Once detached from the tree, citrus fruits undergo several changes, including respiration, transpiration, and the continued ripening process [19]. Respiration involves the conversion of stored sugars into energy, leading to the production of carbon dioxide and water [20]. This process is influenced by temperature, and improper storage conditions can lead to increased respiration rates, affecting fruit quality (Table 1) [21]. Transpiration, the loss of water through the fruit's skin, can lead to dehydration and shriveling if not controlled [22]. The use of wax coatings or humidity control can mitigate this effect [23]. The ripening process continues post-harvest, with enzymes breaking down starches and acids, leading to changes in color, flavor, and texture [24]. Understanding and managing these processes are essential for maintaining quality and consumer appeal.

Several key factors influence the post-harvest physiology of citrus fruits, contributing to their appearance, flavor, and shelf life:

1. **Temperature Control:** Temperature is critical in regulating respiration and ripening rates, and improper temperature management can lead to disorders like chilling injury in cold-sensitive citrus varieties [27].
2. **Humidity Levels:** Controlling humidity is essential to prevent excessive water loss, which can lead to shriveling and weight loss [28].
3. **Ethylene Exposure:** Ethylene, a natural ripening hormone, can accelerate ripening and softening. Managing exposure to ethylene is vital for controlling the ripening process, particularly during storage and transportation [29].
4. **Chemical Treatments:** Various post-harvest treatments, such as fungicides and wax coatings, are used to prevent decay and maintain appearance. Understanding the correct application and potential residues is essential for compliance with regulations and consumer safety [30].
5. **Handling Practices:** Gentle handling during harvesting, sorting, and packaging minimizes mechanical injuries that can lead to decay or other quality issues [31].
6. **Cultivar Specifics:** Different citrus varieties may have unique post-harvest requirements, and understanding these specific needs can aid in optimizing quality [32].

Table 1. Recommended temperature ranges, relative humidity (RH) values, and approximate storage lives for citrus fruit species

Citrus Species and Variety	Temperature Range (°C)	RH %	Approximate Storage Life
Grapefruit	10–15	85–90	6–8 weeks
Lemon	10–13	85–90	1–6 months
Limes	9–10	85–90	6–8 weeks
Mandarin hybrids (Fortune, Nova)	8–9	85–90	4–6 weeks
Mandarin, Tangelo	5–6	90–95	2–4 weeks
Clementine, Satsuma	4–5	90–95	2–4 weeks
Kumquat	4–5	90–95	2–4 weeks
Pigmented orange	6–8	90–95	3–8 weeks
Blond orange	3–9	85–90	3–8 weeks

Source: [25], [26].

Key factors influencing post-harvest physiology

3. COMMON POST-HARVEST PHYSIOLOGICAL DISORDERS

i. Chilling Injury: Chilling Injury (CI) is a common disorder affecting citrus fruits stored at low temperatures. Symptoms include surface pitting, discoloration, water-soaked areas, and internal browning [33]. CI is particularly problematic in cold-sensitive citrus varieties, such as oranges and grapefruits, and can lead to the loss of quality and marketability [34]. CI results from exposure to low but non-freezing temperatures over an extended period. This leads to changes in membrane integrity, enzyme activities, and metabolic processes, causing visible symptoms [35]. The sensitivity to chilling varies among citrus species and cultivars [36]. CI can lead to off-flavors and texture changes, reducing consumer appeal and market value [37]. The economic impact can be substantial, particularly for exported fruits [38].

ii. Rind Staining: Rind staining is a disorder characterized by undesirable brown or yellowish spots on the fruit's rind. This disorder can be attributed to mineral imbalances, particularly an excess of manganese or a deficiency of zinc [39]. Rind staining negatively affects the fruit's appearance, and even though it doesn't always affect the internal quality, it can reduce market acceptance [40]. The exact mechanisms behind rind staining are not fully understood, but mineral imbalances, improper irrigation, and specific soil conditions are often implicated [41]. Proper nutrient management can mitigate this disorder [42]. Despite not always affecting internal quality, rind staining reduces visual appeal, leading to lower market grades and prices [43].

iii. Water Loss and Shrivel: Water loss and shriveling occur when the fruit loses moisture, leading to the collapse of cells and the wrinkling of the skin. This disorder is influenced by relative humidity, temperature, and the fruit's maturity stage at harvest [44]. Excessive water loss can cause a weight reduction and textural changes that decrease consumer appeal [45]. Factors such as improper storage humidity, excessive ventilation, and the absence of wax coatings contribute to water loss. The loss of turgor pressure leads to the shriveling appearance [46]. These disorders cause a loss in weight and textural quality, diminishing market value [47].

iv. Mold and Decay: Mold and decay are caused by various fungal and bacterial pathogens that infect the fruit, often through wounds or natural openings. Common pathogens include *Penicillium spp*., causing green or blue mold, and Geotrichum candidum, leading to sour rot [48]. These disorders can rapidly spread, leading to significant losses if not controlled [49]. Infections occur through wounds or natural openings and are exacerbated by high humidity, poor ventilation, and improper handling. Preventive measures include sanitation, temperature control, and chemical treatments [50]. Infected fruits are often unmarketable, leading to complete losses. The spread of pathogens can affect other fruits in storage or transit, leading to larger-scale losses [51].

4. DETECTION AND DIAGNOSIS OF DISORDERS

Detecting and diagnosing post-harvest disorders in citrus fruits have been an evolving field. Traditional methods have long been the mainstay in this area, relying primarily on visual inspection, sensory analysis, and basic laboratory tests. Skilled personnel would painstakingly examine the fruits for physical symptoms such as discoloration, soft spots, mold, or shriveling [52]. The use of taste and smell to detect off-flavors or odors associated with specific disorders or decay was also common [53]. These methods, though proven, were time-consuming and had limitations in efficiency, accuracy, and the ability to detect internal or latent defects [54].

The last few decades have seen a significant shift towards more sophisticated and accurate methods. Modern technologies and innovations have allowed for non-destructive, rapid, and reliable results [55]. Near-Infrared Spectroscopy (NIRS) emerged as a powerful tool for detecting internal quality parameters such as sugar content, acidity, and internal disorders without damaging the fruit [56]. X-ray imaging allowed for the visualization of internal structures, and electronic nose and tongue systems mimicked human sensory perception to provide objective assessments of flavor and aroma [57]. The integration of machine learning and computer vision with imaging techniques allowed automated and precise sorting and grading based on visual defects or quality parameters. Molecular techniques like PCR identified specific pathogens at very early stages, enabling targeted interventions. Despite these advances, implementing modern technologies comes with challenges. Many disorders or infections may not exhibit visible symptoms until later stages, making early detection difficult. The cost and accessibility of advanced techniques might be prohibitive for small-scale growers or those in developing regions. The complexity of these methods often requires specialized training and understanding, creating barriers to widespread adoption [58]. Ensuring uniform standards across different markets or regions, and compliance with regulatory requirements, adds complexity to the detection process. Additionally, integrating new technologies with existing post-harvest handling practices necessitates careful planning and adaptation.

5. PREVENTION AND MANAGEMENT STRATEGIES

Prevention and management of post-harvest physiological disorders in citrus fruit crops necessitate a holistic approach, considering factors ranging from pre-harvest conditions to post-harvest handling, storage, and transportation. The choice of citrus varieties, soil management, fertilization, irrigation, and pest control play a crucial role in minimizing post-harvest disorders. Selecting disease-resistant and climate-adapted varieties can significantly reduce susceptibility to common disorders like chilling injury or mold [59]. Proper nutrient management, particularly calcium, aids in strengthening cell walls, reducing the risk of water loss, and shrivel. Controlled irrigation, particularly during the final maturation stages, can prevent issues like rind staining. Proper harvesting methods and timing are paramount in maintaining the quality and shelf life of citrus fruits. Harvesting at the correct maturity stage, gentle handling to minimize bruises and prompt cooling are essential for maintaining quality. Timing the harvest to avoid temperature extremes can reduce the risk of chilling injuries [60]. Various treatments and technologies are applied on post-harvest to extend shelf life and preserve quality. These include waxing to reduce moisture loss, controlled atmosphere storage to slow down respiration and ripening, and heat treatments to control decay. The application of edible coatings enriched with antimicrobial compounds offers a promising avenue for enhancing shelf life. Proper storage conditions are vital in preventing or slowing down post-harvest physiological disorders. Temperature, humidity, and air circulation must be carefully controlled to prevent both chilling injury and mold growth. Transporting citrus fruits under controlled conditions, with attention to temperature, humidity, and handling, ensures that the quality is maintained until reaching the consumer. Traditional chemical treatments, such as fungicides, have been widely used to control decay. However, there's a growing interest in biological control methods using antagonistic microorganisms or natural substances [61]. Combining chemical and biological controls, in what is known as integrated pest management (IPM), offers an effective and environmentally sustainable approach [62]. Emerging technologies are paving the way for innovative prevention and management strategies. Advances in genomics are enabling the development of genetically modified citrus varieties with enhanced resistance to specific disorders [63]. Similarly, the application of nanotechnology in packaging offers potential benefits in maintaining optimal humidity and controlling microbial growth [64].

6. ECONOMIC AND ENVIRONMENTAL IMPLICATIONS

Post-harvest physiological disorders in citrus fruits significantly impact the economy, resulting in direct and indirect losses. Direct losses stem from reduced market value and rejection of affected fruits, which may account for up to 20% of total production in some regions [65]. Indirect losses are seen in increased costs for sorting, grading, and disposal of affected fruits, along with additional treatments to minimize disorders. These disorders often lead to reduced export opportunities, impacting trade balances and economic stability in citrus-growing regions. The economic implications also trickle down to the labor market, with reduced demand for workers in affected farms and processing facilities [66]. The environmental implications of post-harvest management strategies for citrus fruits are multifaceted. Traditional chemical treatments, such as fungicides and growth regulators, have long been associated with environmental pollution and potential health risks. They may contaminate soil and water bodies, affecting non-target organisms. On the other hand, biological controls and integrated pest management strategies offer environmentally friendly alternatives but may present challenges in terms of scalability and efficacy [67]. Technologies such as controlled atmosphere storage and waxing can reduce food waste, contributing to sustainability. However, these technologies may have energy-intensive requirements, thereby contributing to greenhouse gas emissions. Modern packaging materials, while effective in maintaining quality, can add to the global problem of plastic pollution unless biodegradable options are used. Sustainability in managing post-harvest physiological disorders in citrus fruits encompasses economic, social, and environmental aspects. The goal is to achieve an optimal balance between maintaining quality and market value while minimizing negative environmental impacts and promoting social welfare. From an economic standpoint, sustainable practices entail efficient utilization of resources, reducing waste, and enhancing market access through compliance with international standards and certifications [68]. Implementing traceability systems can foster transparency and trust along the supply chain, benefiting both producers and consumers.

Environmental sustainability requires a shift towards eco-friendly practices, such as organic farming, biological controls, renewable energy in storage and transportation, and sustainable packaging solutions. Collaborative efforts involving governments, industry, academia, and non-governmental organizations are essential to facilitate this transition [69]. Social sustainability focuses on fair labor practices, education, and community engagement. Ensuring fair wages, safe working conditions, and access to training and education fosters social cohesion and long-term sustainability in citrus-growing communities [70]. Emerging trends such as circular economy concepts, where waste materials are reintegrated into the production process, offer innovative pathways for sustainable management of post-harvest disorders in citrus fruits. Developing robust models to assess the life cycle impact of different management strategies enables informed decision-making, aligning economic gains with environmental stewardship and social responsibility [71].

7. FUTURE PERSPECTIVES AND RESEARCH GAPS

The understanding and management of post-harvest physiological disorders in citrus fruits are dynamic fields with much left to explore. As the global demand for citrus fruits continues to grow, so does the necessity for innovative solutions and an understanding of emerging trends, research needs, and implications for various stakeholders. Emerging technologies play a critical role in reshaping the management of post-harvest disorders in citrus fruits. Innovations such as nanotechnology offer unprecedented opportunities for improving packaging materials to enhance shelf life and maintain quality [72]. Novel biological controls using genetically engineered organisms present potential solutions for reducing chemical reliance, thereby minimizing environmental impacts. Sensing technologies based on artificial intelligence and machine learning are paving the way for real-time monitoring of storage conditions and early detection of disorders, enabling timely interventions. The growing consumer demand for organic and sustainably produced fruits is driving changes in post-harvest management strategies. There's a move towards more natural treatments, including the use of plant extracts (Table 2) and essential oils, which have shown promising results in controlling various post-harvest disorders [73]. These approaches align with the global push for sustainable agriculture and are likely to gain traction in the coming years. While there has been substantial progress in understanding and managing post-harvest disorders in citrus fruits, several research gaps and opportunities exist. There's a need for more in-depth studies on the underlying molecular mechanisms that lead to specific disorders, such as chilling injury or rind staining. Such knowledge could facilitate the development of targeted interventions and preventive measures [74]. Research into alternative and eco-friendly treatments is an area ripe for exploration. Further studies are needed to validate the efficacy of biological controls and natural substances, their compatibility with existing management practices, and potential impacts on fruit quality and consumer acceptance [75].

The development and validation of predictive models that can forecast the risk of disorders based on pre-harvest conditions, climatic factors, and market trends present an exciting research avenue. These models could be instrumental in decision-making processes for growers, marketers, and policymakers [76].

8. IMPLICATIONS FOR GROWERS, RESEARCHERS, AND POLI-CYMAKERS

The future perspectives in post-harvest management of citrus fruits have broad implications for various stakeholders.

Table 2. Efficacy of plant extracts on postharvest decay control in citrus fruit

Extracts	Fruit Tested	Target Pathogens	Significant Results	References
Cinnamaldehyde	Mandarins	*Penicillium digitatum, Galactomyces* citri-aurantii	Strong antifungal properties; green mould and sour rot (*G. citri-aurantii*) reduced incidence; induced defence responses in citrus fruit	[25]
Citronellal	Oranges	*P. digitatum*	Reduced postharvest incidence of green mould in citrus fruit	[25]
Garlic	Oranges	*P. digitatum, P. italicum*	Higher increased activity in mixed garlic extracts with oils	[26]
Isothiocyanates	Mandarins	*G. citri-aurantii*	Antifungal properties both in vitro and in vivo conditions	[25]
Propolis	Mandarins	*Penicillium digitatum, P. italicum.*	Reduced green mould (*P. digitatum*) and blue mould (*P. italicum*) incidence in wound-inoculated fruit and naturally infected fruit	[26]
Solanum nigrum	Lemons	*P. digitatum*	In vitro antifungal activity Preventive antifungal efficacy in artificially wounded fruit	[26]
Cistus plant extracts	Mandarins	*G. citri-aurantii*	Antifungal properties in both in vitro and in vivo conditions	[26]
Pomegranate (Punica granatum L.) peel extract	Lemons	Primary postharvest pathogens in citrus fruit (in vitro tests)	Strong efficacy of in vitro and in vivo treatments due to the high content of phenolic compounds	[25]
T. leptobotrys, C. villosus, E. globulus and P. harmala extracts	-	*P. digitatum, P. italicum, G. citri-aurantii*	High antifungal activity in in vitro tests	[26]

Growers: They stand to benefit from the adoption of innovative technologies and practices that enhance fruit quality and reduce losses. However, they must navigate challenges related to accessibility, affordability, and adaptability of these new solutions [77].

Researchers: They are at the forefront of driving innovations and addressing research gaps. Collaborative efforts involving multidisciplinary teams, including experts in agriculture, biotechnology, economics, and social sciences, are vital for developing comprehensive solutions [78].

Policymakers: They play a crucial role in shaping the regulatory landscape that governs the adoption of new technologies and practices. Policies that promote research, incentivize sustainable practices, and ensure fair trade can foster a resilient citrus industry [79].

9. CONCLUSION

The management of post-harvest physiological disorders in citrus fruits is a complex and vital aspect of global agriculture. Emerging technologies, innovative research, and sustainable practices present promising avenues for addressing challenges and enhancing quality. However, realizing this potential requires concerted efforts from growers, researchers, policymakers, and other stakeholders. Collaborative initiatives, investments in research, and alignment with sustainability goals are essential to ensuring that the citrus industry continues to thrive, meeting both economic and environmental imperatives. The future holds great promise, provided that the intricate balance between innovation and responsibility is maintained.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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