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Fresh Strategies in Post-Harvest Handling of Mangoes: Cutting-Edge Approaches to Minimize Losses

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Abstract:

Mango, one of the most widely consumed tropical fruits, faces significant post-harvest losses due to improper handling, microbial contamination, and environmental factors. These losses threaten both global supply chains and the profitability of mango producers. This article reviews advancements in post-harvest technologies, including Modified Atmosphere Packaging (MAP), cold chain management, and innovative packaging solutions, that have significantly improved the shelf life and quality of mangoes. Additionally, the article explores biological and natural methods, such as edible coatings and the use of plant extracts, to reduce spoilage. The integration of automation, non-destructive testing (NDT) methods, and AI-driven technologies is enhancing sorting and grading processes, improving efficiency and reducing human error. The article concludes by emphasizing the need for continued research and the adoption of sustainable practices, such as blockchain and energy-efficient systems, to ensure the future success of the mango industry in reducing post-harvest losses.

1. Introduction:

1.1. Importance of Mango as a Global Fruit Crop

Mango (Mangifera indica) is one of the most significant tropical fruits globally, ranking among the top fruits in terms of production and consumption. Known as the "king of fruits," it is not only an important food crop but also a valuable economic commodity, contributing to the livelihoods of millions of farmers. Mangoes are grown in leading producer, followed by countries such as China, Thailand, Indonesia, and the Philippines. The fruit's rich flavor, vibrant

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color, and nutritional value, including high levels of vitamin C, fiber, and antioxidants, make it popular worldwide, both in fresh and processed forms. Mangoes are consumed in a variety of ways, from being eaten fresh to processed into juices, jams, dried fruit, and other products.

1.2. Overview of Post-Harvest Losses in Mangoes

Despite its high demand and importance, mangoes are highly perishable and subject to significant post-harvest losses. According to various studies, up to 25% to 40% of mangoes are lost from farm to market due to inadequate post-harvest handling practices. These losses occur at various stages of the supply chain, including during harvesting, transportation, storage, and processing. The primary factors contributing to these losses include mechanical damage, physiological disorders, microbial infections, and inadequate temperature and humidity control. In developing countries, where infrastructure for cold storage and transportation is lacking, the post-harvest losses can be even more pronounced.

1.3. Need for Improved Post-Harvest Handling Practices to Reduce Losses

The need for improved post-harvest handling practices is critical to minimizing losses and enhancing the quality and shelf-life of mangoes. Effective post-harvest management systems can help increase the availability of mangoes, improve market access, and boost the profitability of mango farming. The implementation of advanced handling technologies can reduce food waste, increase the economic value of mango exports, and contribute to food security globally.

2. Current Challenges in Mango Post-Harvest Handling

2.1. Types of Post-Harvest Losses

Post-harvest losses in mangoes can be broadly categorized into the following types:

1. **Physical Damage:** Physical damage occurs due to mishandling during harvesting, transportation, and packaging. Bruising, punctures, and cuts expose the fruit to contamination, leading to a shorter shelf life and poor quality. This is particularly common when mangoes are not handled gently or when inappropriate harvesting tools are used.
2. **Microbial Contamination:** Mangoes are highly susceptible to microbial infections, particularly fungal pathogens like Colletotrichum gloeosporioides (responsible for anthracnose), and Lasiodiplodia theobromae (which causes stem-end rot). These fungi can invade the fruit, causing it to rot quickly, making it unsuitable for sale.

3. **Physiological Changes:** Mangoes are climacteric fruits, meaning they ripen and continue to produce ethylene even after harvesting. This can lead to rapid softening, discoloration, and other physiological disorders like chilling injury, which occurs when mangoes are stored at low temperatures for extended periods. Additionally, over-ripening can result in a loss of flavor, texture, and nutritional value.
4. **Chemical Deterioration:** Chemical deterioration involves the breakdown of nutrients like vitamin C and other antioxidants due to exposure to high temperatures or improper handling. Mangoes also release significant amounts of ethylene during ripening, which accelerates the ripening of neighboring fruits if not controlled.

2.2. Factors Contributing to Post-Harvest Losses

Several factors contribute to the extent of post-harvest losses in mangoes:

1. **Improper Harvesting Practices:** Mangoes should be harvested at the appropriate maturity stage to ensure optimal quality. Harvesting too early or too late can lead to poor fruit quality and reduced shelf life. Additionally, harvesting methods that involve improper handling or use of inappropriate tools can cause bruising and cuts.
2. **Inadequate Storage Conditions:** Mangoes require specific temperature and humidity conditions for storage to slow down ripening. The lack of cold storage facilities, especially in developing countries, accelerates spoilage and reduces the fruit's marketability.
3. **Inefficient Transportation:** Mangoes are often transported in conditions where temperature control is not maintained, resulting in quicker ripening and a higher risk of spoilage. Mechanical damage during transit due to rough handling or inadequate packaging also contributes to losses.
4. **Insufficient Packaging Materials:** Conventional packaging materials may not provide adequate protection to mangoes from physical damage, dehydration, or microbial contamination. Poorly designed packaging that does not account for ventilation and moisture control can hasten deterioration.

3. Advancements in Mango Post-Harvest Handling Technologies

3.1. Modified Atmosphere Packaging (MAP) and Controlled Atmosphere (CA) Storage

Modified Atmosphere Packaging (MAP) and Controlled Atmosphere (CA) storage are widely used technologies to extend the shelf life of mangoes by altering the composition of gases around the fruit.

1. **Benefits of MAP and CA:** MAP uses packaging materials that control the gas exchange between the fruit and the external environment, reducing the concentration of oxygen (O_2) and increasing carbon dioxide (CO_2) around the fruit. This slows down respiration, delaying ripening and extending the shelf life. Similarly, CA storage involves storing mangoes in a controlled environment with specific levels of oxygen, carbon dioxide, and humidity to preserve fruit quality for longer periods.
2. **Recent Innovations and Applications:** Recent advancements in packaging materials, such as nano-structured films, have enhanced gas permeability control, improving the efficiency of MAP. Additionally, intelligent packaging with sensors allows real-time monitoring of the fruit's condition during transportation and storage, ensuring that optimal storage conditions are maintained.

3.2.Cold Chain Technology

Cold chain technology plays a critical role in preventing rapid ripening and spoilage of mangoes by maintaining a consistent low temperature during storage and transportation.

1. **Impact of Temperature Control:** Maintaining temperatures between 12-13°C helps reduce respiration and delay the onset of ripening. Mangoes stored at lower temperatures also show a reduction in microbial activity, further prolonging shelf life.
2. **Advances in Cold Storage Techniques:** The integration of IoT-based monitoring systems has revolutionized cold storage management. Real-time tracking of temperature and humidity levels helps maintain optimal conditions, reducing the risk of temperature fluctuations that could lead to spoilage. Additionally, hydro-cooling methods are increasingly being used to quickly cool mangoes after harvest, reducing heat buildup and extending freshness.

3.3.Packaging Innovations

New materials and designs for mango packaging have significantly improved the protection of mangoes during transportation and storage.

1. **Ventilated Packaging:** Packaging with built-in ventilation holes allows for better air circulation around the

mangoes, reducing the buildup of ethylene and moisture. This not only extends shelf life but also helps prevent the growth of mold and mildew.

2. **Biodegradable Packaging Materials:** The use of eco-friendly, biodegradable packaging materials such as plant-based plastics and biodegradable films is becoming more common. These materials provide a sustainable alternative to traditional plastic and help reduce the environmental impact of packaging waste.

3.4. Ethanol Vapour Treatments and Other Chemical Methods

Chemical methods like ethanol vapor treatments are widely used to delay ripening and extend the shelf life of mangoes.

1. **Effectiveness of Ethanol Vapour:** Ethanol vapor has been shown to reduce the rate of ethylene production in mangoes, slowing down ripening and reducing the incidence of fungal infections.
2. **New Chemical Strategies and Their Safety:** Recent research has focused on developing safe, GRAS (Generally Recognized as Safe) chemicals to delay ripening and improve fruit quality. These include natural plant-based compounds such as cinnamic acid and citric acid, which help in extending shelf life without harmful side effects.

4. Biological and Natural Methods for Reducing Post-Harvest Losses

4.1 Use of Natural Coatings and Edible Films

The application of natural coatings and edible films on mangoes provides a protective layer that helps to maintain fruit moisture, reduce microbial growth, and extend shelf life.

1. **Benefits of Edible Coatings for Shelf-Life Extension:** Edible coatings made from chitosan, pectin, and whey proteins can significantly reduce water loss and prevent microbial contamination. These coatings form a barrier to oxygen, which helps to preserve the fruit's freshness and texture.

4.2. Use of Plant Extracts and Essential Oils: Plant extracts and essential oils with antimicrobial and antifungal properties are increasingly being used as natural preservatives for mangoes.

1. **Anti-Microbial and Anti-Fungal Properties:** Essential oils derived from thyme, clove, cinnamon, and oregano are known to inhibit the growth of fungi and bacteria that cause spoilage. Additionally, extracts from plants such as neem and garlic are being explored

for their potential in reducing post-harvest diseases in mangoes.

4.3. Probiotic Applications

Beneficial microorganisms such as Lactobacillus and Bacillus subtilis are being tested as natural biocontrol agents to prevent spoilage in mangoes. These probiotics can inhibit the growth of pathogenic fungi, improving fruit shelf life without the use of chemicals.

5. Quality Control and Sorting Technologies

5.1. Automation in Sorting and Grading

Automated sorting and grading technologies have revolutionized the post-harvest handling of mangoes by improving efficiency, reducing human error, and ensuring consistent product quality. Automated systems use advanced sensors, cameras, and robotics to perform sorting based on factors such as size, color, shape, and ripeness. This ensures that only high-quality mangoes make it to the market, reducing waste and increasing consumer satisfaction.

Advances in Optical Sorting Technologies

Optical sorting systems have evolved significantly in recent years. These systems use high-resolution cameras combined with **near-infrared (NIR)** and **hyperspectral imaging** technologies to assess the external and internal quality of mangoes. NIR sensors help detect the internal ripeness, sugar content, and firmness of the fruit without damaging it. By employing artificial intelligence algorithms, optical sorting systems can distinguish between different levels of ripeness, ensuring that mangoes are graded precisely and consistently.

Machine Learning Applications for Quality Assessment

Machine learning (ML) techniques are increasingly being integrated into sorting systems to enhance their ability to assess fruit quality. ML algorithms analyze data collected from optical sorting systems to identify patterns and classify mangoes based on ripeness, internal defects, or bruising. Over time, these systems "learn" from large datasets, becoming more accurate and capable of detecting subtle defects that might go unnoticed by human inspectors. The use of machine learning can lead to improvements in both the speed and accuracy of mango sorting, ensuring better-quality products reach consumers.

5.2 Non-Destructive Testing (NDT) Methods

Non-destructive testing (NDT) technologies are vital in assessing the internal quality of mangoes without causing damage. These methods allow for real-time analysis of factors like firmness, sugar content, and overall fruit health.

Technologies for Assessing Internal Fruit Quality

Several NDT technologies are being explored for mango post-harvest handling, including:

1. **Firmness Sensors**: Tools like **penetrometers** and **ultrasonic waves** are used to measure the firmness of mangoes. These sensors can identify overripe or under-ripe mangoes without the need for cutting or damaging the fruit.
2. **Brix Measurement**: **Refractometers** and **NIR sensors** are commonly used to measure the Brix value, an indicator of the sugar content in mangoes. This data helps determine ripeness and sweetness, essential factors for consumers.
3. **X-ray Imaging**: Advanced X-ray imaging techniques can detect internal defects like seed damage or rot, allowing for the removal of suboptimal fruit before they reach consumers. This technology helps preserve overall fruit quality by minimizing the risk of selling damaged or spoiled mangoes.

6. Integrated Post-Harvest Management Systems

6.1 Overview of Integrated Approaches for Handling Mangoes

An integrated post-harvest management system involves the combination of various strategies to optimize the handling, storage, and transportation of mangoes. This approach typically includes:

1. **Cold Storage**: The use of cold storage technologies to maintain an ideal temperature and humidity range for mangoes.
2. **Packaging Solutions**: Advanced packaging materials, such as breathable films and ventilated crates, that protect mangoes from physical damage while maintaining freshness.
3. **Chemical and Biological Treatments**: Incorporating strategies like ethanol vapor treatments or natural coatings to prolong shelf life and prevent microbial contamination.

By combining these practices in a coordinated manner, integrated systems provide more comprehensive post-harvest solutions, reducing losses and maintaining fruit quality across the supply chain.

6.2. Benefits of Combining Various Strategies

The integration of various technologies and methods ensures a holistic approach to mango post-harvest handling. The key benefits of an integrated system include:

1. **Reduced Waste and Losses**: By utilizing cold storage, proper packaging, and treatment methods, mangoes maintain their quality and are less likely to spoil during transport.

This directly translates into reduced post-harvest losses.

2. **Enhanced Efficiency**: Automation, NDT, and machine learning technologies can be used in conjunction to speed up sorting and grading processes, reducing the reliance on manual labor and decreasing the time required for processing.
3. **Improved Shelf Life and Quality**: The combination of appropriate temperature control, packaging, and treatments ensures that mangoes remain fresh for a longer period, making them more suitable for export and retail markets.

6.3.Case Studies of Successful Implementations

Several successful case studies highlight the positive impact of integrated systems on mango post-harvest handling.

1. **India's Mango Export Industry**: In India, a leading mango exporter, the integration of cold storage facilities, proper handling practices, and packaging improvements has allowed mangoes to reach international markets with minimal losses. This integrated approach has contributed to India's position as one of the largest mango exporters globally.
2. **Thailand's Automated Sorting Systems**: Thailand has implemented automated optical sorting systems to streamline the grading process for mangoes. This integration of sorting technologies with cold chain management has drastically reduced the time mangoes spend in transit and improved overall fruit quality.

Conclusion

In conclusion, post-harvest losses in mangoes can be minimized through the adoption of advanced technologies such as MAP, cold chain management, and new packaging materials. Additionally, biological methods and the integration of AI and IoT into post-harvest processes are playing a critical role in improving mango quality and reducing waste. Sustainable practices, including eco-friendly packaging and energy-efficient cold storage systems, are also essential in addressing the environmental impact of mango post-harvest handling. For the mango industry to remain competitive globally, stakeholders must invest in these innovations and collaborate to implement integrated systems that reduce losses, improve product quality, and promote sustainability.

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