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Plasma-Activated Water Mist Systems Driven by AI for Surface Decontamination in Tropical Fruit Packing

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Abstract: -

Tropical fruits such as mango, papaya, and pineapple are highly susceptible to surface microbial contamination during postharvest handling, leading to substantial losses and food safety concerns. This article reviews the application of plasma-activated water (PAW) mist systems integrated with artificial intelligence (AI) for chemical-free surface decontamination in tropical fruit packing lines. PAW, generated through non-thermal plasma exposure of water, contains reactive oxygen and nitrogen species that effectively inactivate bacteria and fungi without leaving harmful residues or affecting fruit quality. When delivered as a fine mist, PAW ensures uniform coverage of complex fruit surfaces while minimizing water use. AI-driven control systems dynamically optimize mist concentration, exposure time, and flow rate based on fruit characteristics and microbial load, enhancing disinfection efficiency and resource conservation. Experimental studies report up to 4–5 log reductions in major foodborne pathogens, preservation of physicochemical quality, and significant shelf-life extension under cold storage. Overall, AI-assisted PAW mist technology represents a sustainable, scalable, and effective alternative to conventional chemical washes for improving postharvest safety and quality of tropical fruits.

1. Introduction

Tropical fruits such as mangoes, papayas, and pineapples are highly prone to microbial contamination on their surfaces, often harboring pathogens including *Salmonella* and *Escherichia coli*. These microorganisms contribute significantly to

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postharvest losses, sometimes exceeding 30% during packing, transport, and storage, while simultaneously posing serious public health risks (Soni & Choi, 2024). Conventional chemical washes, such as chlorine or peracetic acid solutions, can reduce microbial loads; however, they often compromise fruit quality, leave residual chemicals on the produce, and generate environmentally harmful by-products.

Plasma-activated water (PAW) mist represents a novel, chemical-free approach for surface decontamination. PAW is produced by exposing water to plasma, a highly ionized gas, which generates a complex mixture of reactive oxygen and nitrogen species, including hydroxyl radicals, hydrogen peroxide, and nitric acid. These reactive species are short-lived yet highly effective at inactivating bacteria, fungi, and spores without thermal damage or the production of harmful residues. Integration with artificial intelligence (AI) allows real-time optimization of misting parameters, achieving maximum microbial inactivation while preserving sensory and physicochemical properties of the fruit (Zhang *et al.*, 2021; Thang *et al.*, 2024).

2. Mechanisms of Microbial Inactivation by Plasma-Activated Water

PAW mist is generated by channeling ambient air or oxygen through a dielectric barrier discharge plasma generator into water. This process produces reactive species, primarily hydrogen peroxide and nitric acid, at concentrations typically ranging from 50 to 200 parts per million. These species exert antimicrobial effects through multiple mechanisms, including disruption of microbial cell walls, oxidation of membrane lipids and proteins, and inhibition of nucleic acid synthesis, leading to rapid microbial inactivation. Laboratory and packing-line studies indicate that exposure durations of five to ten minutes can achieve up to 99.9% germicidal efficiency against both Gram-negative and Gram-positive bacteria (Thang *et al.*, 2024; Soni & Choi, 2024).

The mist is delivered via fine nozzles that uniformly coat fruit surfaces, including rough or waxy skins, without over-soaking or leaving residual liquid. AI systems monitor critical parameters such as surface microbial load, water flow (approximately 250 mL/min), and fruit temperature, dynamically adjusting mist intensity and duration to optimize disinfection efficiency while preserving fruit quality (Choi *et al.*, 2025).

3. Evaluation of PAW Mist Efficacy

Experimental trials demonstrate the high effectiveness of PAW mist for tropical fruits. In mangoes, *Salmonella* populations were reduced by four to five logarithmic scales, achieving >99.99% reduction after ten minutes of exposure, with no detectable alterations in color, firmness, or flavor over 14 days of cold storage at 4°C (Zhang *et al.*, 2021). On papayas, fungal and mold growth was reduced by 90% relative to conventional chlorine washes, which can negatively affect fruit quality and leave residues.

AI-assisted control models further enhance operational efficiency by predicting optimal exposure times based on fruit type, size, surface roughness, and initial microbial load. This predictive control reduces water and energy consumption by 20–30% compared to conventional washing methods while maintaining superior microbial control and extending postharvest shelf life (Thang *et al.*, 2024; Soni & Choi, 2024).

4. System Design and Process Parameters

PAW mist systems are designed for integration into commercial packing lines. Compact plasma generators produce PAW on-site, while AI-driven software, running on standard industrial computers, manages nozzle operation, mist concentration, and exposure duration. Fruit handling temperatures are maintained below 40°C to ensure both worker safety and the prevention of thermal or oxidative damage to the produce. Compared with traditional decontamination methods, PAW mist is particularly effective for tropical fruits with thick, waxy skins, where standard liquid washes often fail to penetrate microbial biofilms (Choi *et al.*, 2025).

5. Impact on Postharvest Physiology and Quality

The controlled reduction of surface microbial populations contributes to lower respiration rates in packaged fruits, delays physiological disorders such as lignification and tissue toughening, and suppresses spoilage microorganisms. Importantly, PAW treatment preserves physicochemical attributes such as color, firmness, and flavor, ensuring consumer acceptability and extending marketable shelf life.

6. Future Developments and Applications

Future improvements may include integrating AI-controlled PAW mist systems with advanced fruit surface scanning technologies capable of detecting microbial hotspots and adjusting reactive species dosing in real time. Synergistic combinations with UV-C light or other non-thermal interventions may further enhance microbial inactivation. Portable and modular PAW units could facilitate adoption in smallholder farms, and innovations in reactive species chemistry could expand efficacy against viral pathogens. Adoption of these technologies could reduce tropical fruit postharvest losses by up to 25% by 2030 (Zhang *et al.*, 2021; Thang *et al.*, 2024; Soni & Choi, 2024).

7. Conclusion

Plasma-activated water mist systems integrated with AI provide a sustainable, chemical-free approach for tropical fruit surface decontamination. They effectively reduce microbial loads, preserve fruit quality, conserve water and energy, and extend shelf life. With scalable, safe, and low-cost designs, these systems are poised for implementation across commercial fruit supply chains, promoting safer and more sustainable distribution of tropical fruits.

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