Mechanistic Study of 150 W Cold Plasma Treatment for the Preservation of Hongyan Strawberries: Pesticide Degradation and Microbial Inhibition

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Abstract. This study provides the first systematic evaluation of 150 W nonthermal plasma treatment for postharvest strawberry preservation, pesticide residue mitigation, and antifungal activity. Single-factor optimization identified a 7 min exposure as optimal. Berries treated and stored at 25 °C exhibited a significant delay in visible decay: onset shifted from Day 4 in controls to Day 6 after plasma ($p < 0.05$), extending marketable life by ~2 days. At 4 °C, neither treated nor control fruit showed spoilage through 8 days. Plasma had no significant impact on texture metrics or major nutritional components ($p > 0.05$) yet improved sensory taste scores. Surface spoilage fungi—including *Botrytis cinerea*, *Geotrichum candidum*, and isolates related to *Talaromyces verruculosum* identified by ITS rDNA sequencing—were markedly suppressed. Hyphal growth assays showed significant inhibition ($p < 0.05$), and atomic force microscopy revealed severe structural collapse of fungal hyphae after treatment, suggesting membrane/cell wall damage. Critically, a 7 min plasma exposure achieved immediate, complete (100%) degradation of emamectin benzoate residues on berry surfaces. Collectively, the results demonstrate that 150 W plasma, especially at 7 min, offers an effective, residue-reducing, and antifungal intervention to extend the shelf life and safety of fresh strawberries, supporting its promise for practical cold-chain and room-temperature postharvest applications.

Keywords: Plasma, Preservation efficacy, Antibacterial mechanism, Pesticide residue degradation.

1 Introduction

Strawberries (Fragaria × ananassa) are widely appreciated for their sensory appeal and high nutritional value, particularly as rich sources of vitamin C, carbohydrates, dietary fibre, and polyphenolic compounds [1]. However, due to their high water content (approximately 90%) and delicate tissue structure, strawberries are highly perishable, making them vulnerable to microbial spoilage and mechanical damage during postharvest handling and storage [2].

To mitigate fungal infections and insect damage, synthetic pesticides are frequently applied during cultivation. While effective, these applications may result in residual

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pesticide contamination on fruit surfaces [3]. As consumer concerns grow over chemical residues and microbial safety, there is increasing demand for novel, eco-friendly preservation technologies that maintain both food quality and safety [4].

Cold plasma, a non-thermal sterilisation method, has attracted attention for its ability to inactivate a wide spectrum of microorganisms without significantly compromising food quality attributes [5]. Plasma treatment relies on reactive species generated in ionised gases, which can disrupt microbial membranes, degrade chemical residues, and alter biochemical processes.

Despite growing interest in plasma-based interventions for fresh produce, studies specifically targeting the effects of 150 W cold plasma treatment on strawberries—particularly in relation to both microbial control and pesticide degradation—remain limited. Furthermore, the mechanisms underpinning its antifungal activity and impact on fruit quality are not yet fully elucidated.

In this study, we systematically investigate the effects of 150 W cold plasma on postharvest strawberries (cv. Hongyan) using a two-phase experimental design. The objectives are to:

(i) assess the effects of treatment duration and frequency on strawberry shelf life under different storage conditions,

(ii) evaluate changes in quality indicators and nutrient retention,

(iii) identify and assess inhibitory effects on dominant spoilage fungi,

(iv) explore biochemical and morphological mechanisms of fungal inactivation,

(v) examine plasma-induced degradation of emamectin benzoate, a commonly used pesticide.

2 Related Work

In recent years, low-temperature plasma, as a new non-thermal sterilization and pesticide residue degradation technology, has been widely used in the research of fruit and vegetable preservation, especially in the research of strawberry fruits with high moisture and high spoilage rate. Zhao et al. [6] used low-temperature plasma-activated water (PAW) combined with dielectric barrier discharge (DBD) to treat strawberries, and found that the combined method could significantly inhibit the microbial growth on the surface of strawberries under low temperature storage conditions, and maintain the sensory quality and nutrient content of the fruit to a certain extent. In terms of strawberry texture determination, Zhang Weiwei et al. [7] used a texture analyzer to standardize the hardness of strawberries and established a reliable physical index evaluation system, which is helpful to evaluate whether plasma treatment affects the structural stability of strawberries.

In terms of decay-causing fungi, Ma et al. [8] reported for the first time that *Geotrichum candidum* caused rot diseases in strawberry producing areas of China, and its rapid spread and resistance to traditional preservative methods have attracted attention. At the same time, the genome analysis of *Talaromyces verruculosus* by Fu et al. [9] revealed its potential in the degradation of antibiotics, suggesting that it has strong

environmental adaptability and potential risks, which deserve to be monitored during strawberry storage.

In addition, Li et al. [10] further confirmed the differences in the preservation effect of strawberries through plasma treatment with different gas media, and pointed out that the treatment time and gas type have a significant impact on the preservation performance. In addition, the study by Wang et al. [11] showed that low-temperature plasma can also effectively degrade pesticide residues on the surface of fruits and vegetables, such as dimethoate, which provides a theoretical basis and method reference for the degradation of emamectin benzoate in this study.

3 Methodologies

3.1 Quantitative Model for Pesticide Degradation

To characterize the degradation kinetics of emamectin benzoate under plasma exposure, a first-order reaction model was employed as Equation 1.

$$C(t) = C_0 e^{-k_p t}, \tag{1}$$

where $C(t)$ represents the pesticide residue concentration (mg/L) after treatment time t; C_0 is the initial concentration; k_p is the plasma-induced degradation rate constant, and t is the treatment time (min). In the experiment, no residue (i.e., $C(t) \approx 0$) could be detected after 7 minutes of treatment, and it could be reversed to $k_p \geq \frac{-In(0.1/C_0)}{7}$, verifying its rapid decomposition ability.

Strawberries were randomly assigned to experimental groups (n = 10 per group) and placed in sealed containers. The control group (CK) received no treatment. Experimental groups were exposed to plasma for 0.5, 1, 1.5, 3, 5, or 7 minutes, respectively. All samples were stored under two temperature conditions: ambient temperature (25 °C) and refrigeration (4 °C). After an 8-day storage period, fruit decay was visually assessed, and decay rate was calculated using the formula described by Equation 2.

$$\begin{matrix} Decay\ rate\ (\%) \\ = \frac{Number\ of\ decayed\ fruits}{Total\ number\ of\ fruits} \end{matrix} \times 100, \tag{2}$$

Based on preliminary results, treatment durations of 5 and 7 minutes were selected for further investigation. Strawberries were divided into three subgroups: single treatment (Day 0), double treatment (Days 0 and 4), and triple treatment (Days 0, 4, and 8). Storage was conducted for 10 days at 25 °C and 4 °C.

Decay progression was monitored daily at 25 °C. For samples stored at 4 °C, quality assessments were conducted on Days 0 and 10. Textural properties—including firmness, cohesiveness, elasticity, adhesiveness, and chewiness—were measured using a texture analyser. Total soluble solids (TSS) were determined using a handheld digital refractometer, while ascorbic acid (vitamin C) content was quantified via 2,6-dichlorophenolindophenol titration, following GB 5009.86-2016 standards.

3.2 Fungal Inhibition Oxidative Stress Modeling

Spoiled strawberry tissues were aseptically excised and suspended in 9 mL of sterile saline solution. Serial tenfold dilutions were prepared, and 100 µL aliquots were streaked onto potato dextrose agar (PDA) plates for microbial isolation. Colonies were purified and identified via ITS rDNA sequencing using ITS1 and ITS4 primers. Sequencing was performed by Beijing Deaoping Biotechnology Co., Ltd., and results were confirmed through BLAST analysis against the NCBI database.

In order to quantitatively describe the inhibitory effect of plasma on fungal hyphal growth, the following growth inhibition factor was introduced as Equation 3.

$$I_f = 1 - \frac{D_t}{D_0}, \tag{3}$$

where D_0 is the colony diameter of the untreated control group; D_t is the colony diameter of the treatment group; $I_f \in [0,1]$, where $I_f = 1$ indicates complete inhibition.

In addition, based on the protein carbonyl content (PC) and antioxidant enzyme activities (such as SOD, CAT, GSH-Px), the plasma-induced oxidative stress score S_{ox} can be constructed as Equation 4.

$$S_{ox} = \frac{PC}{CAT+SOD+\mathrm{GSH-Px}}, \tag{4}$$

Spore suspensions of the three isolated spoilage fungi were prepared under sterile conditions. After centrifugation (1000 rpm, 10 min), hyphal and spore fractions were separately treated with plasma (5 or 7 minutes), inoculated onto PDA, and incubated at 25 °C. Colony diameters were measured at 24-hour intervals over 72 hours. Untreated spore suspensions served as positive controls, while sterile saline served as the negative control.

Hyphal suspensions were subjected to 5- and 7-minute plasma treatments. Total protein content was measured via the Coomassie Brilliant Blue G-250 method. Oxidative damage was assessed through protein carbonyl quantification using DNPH (2,4-dinitrophenylhydrazine) colorimetric assay. Enzymatic activities of catalase (CAT), superoxide dismutase (SOD), and glutathione peroxidase (GSH-Px) were determined using commercial assay kits (Solarbio Science & Technology Co., Ltd., Beijing, China), as per manufacturer instructions. Fungal hyphae were fixed in 4% glutaraldehyde for 15 minutes, gently washed with deionised water, and imaged using a BRUKER Multimode 8 atomic force microscope. Three-dimensional reconstructions were generated to evaluate ultrastructural damage post-treatment.

Fresh strawberries were divided into four groups: blank control (CK), pesticide-only control (CK1), and plasma treatment groups (5, 7, and 10 minutes post-pesticide application). Emamectin benzoate (5.7% solution) was applied to simulate field-level pesticide residues. Residue analysis was performed every 72 hours using semi-quantitative test strips specific to emamectin benzoate (limit of detection: 0.1 mg/L; OneTest Biotechnology, Beijing, China). Results were interpreted per manufacturer instructions.

4 Experiments

4.1 Effect of Plasma Treatment Duration on Strawberry Shelf Life

The progression of decay under different plasma exposure durations is illustrated in Figure 1. At 25 °C, untreated strawberries (CK) exhibited visible signs of spoilage beginning on Day 4. In contrast, all plasma-treated groups—except the 3-minute group—showed delayed decay onset until Day 6. Notably, the 5- and 7-minute treatment groups maintained significantly lower decay rates throughout the 8-day period ($p < 0.05$), confirming superior preservative efficacy at these exposure durations.

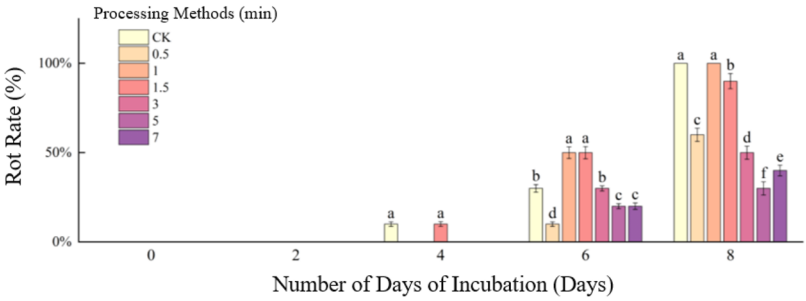

Fig. 1. Plasma gas process under 25 °C incubation for 8 days.

As shown in Figure 2, repeated plasma treatment significantly influenced strawberry decay kinetics under ambient storage. Among all experimental conditions, the group receiving two 7-minute treatments (Days 0 and 4) exhibited the most pronounced inhibition, with decay onset delayed until Day 6—one day later than other groups. This group also maintained the lowest decay rate over the full 10-day period ($p < 0.05$), demonstrating a cumulative antifungal effect with repeated exposure.

These findings indicate that the antifungal efficacy of plasma is not only dose-dependent but also temporally responsive. Reapplication during storage may enhance the persistence of reactive oxygen and nitrogen species (ROS/RNS), thereby extending the protective effect.

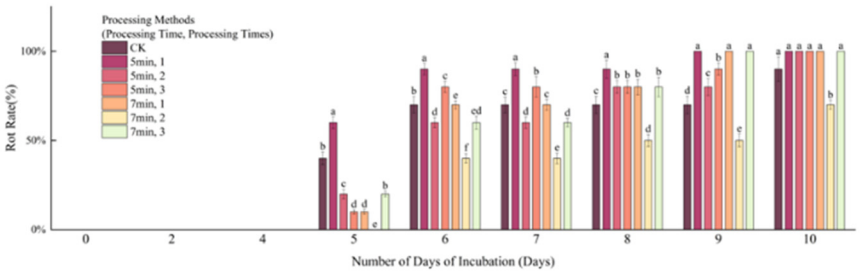

Fig. 2. Different plasma gas processing methods under 25 °C incubation for 10 days.

Three dominant spoilage fungi were successfully isolated from decayed strawberries and identified via ITS rDNA sequencing: *Botrytis cinerea*, *Geotrichum candidum*, and *Talaromyces verruculosus*. Sequence similarity exceeded 99% in BLAST alignments against NCBI reference strains.

Botrytis cinerea, the causative agent of grey mould, is well established as the principal postharvest pathogen in strawberries. *Geotrichum candidum* has recently emerged as a soft rot pathogen in berries, while *Talaromyces verruculosus*—typically known for antibiotic degradation—is herein reported for the first time in the context of strawberry spoilage. The successful isolation and identification of these fungi allow for targeted evaluation of plasma's antifungal effects in subsequent experiments, shown in Figure 3.

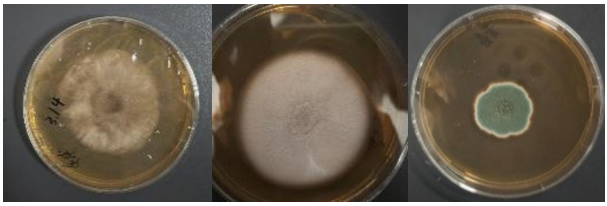

Fig. 3. Isolation of spoilage fungi from the strawberry surface (from left to right: *Botrytis cinerea*, *Geotrichum candidum*, and *Talaromyces verruculosus*).

Plasma treatment significantly inhibited the hyphal growth of all three spoilage fungi in Figure 4. After 72 hours of incubation, *colony* diameters in the treated groups were markedly smaller than in controls ($p < 0.05$), with the 7-minute treatment achieving near-complete growth suppression for *Botrytis cinerea*.

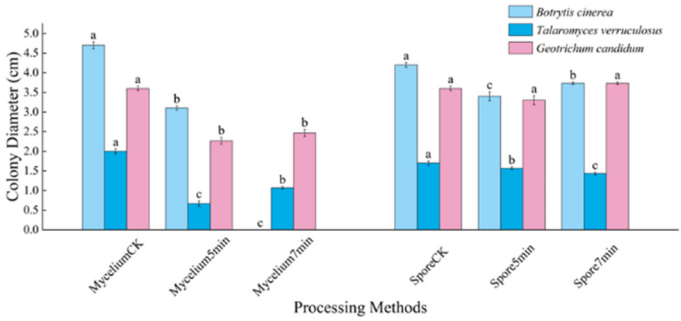

Fig. 4. Comparison of colony diameters of three strawberry spoilage fungi before and after 150 W plasma treatment following 72 h incubation.

Atomic force microscopy (AFM) was employed to visualise ultrastructural changes in *Geotrichum candidum* hyphae following 7-minute plasma treatment. As shown in Figures 5 and 6, treated hyphae displayed pronounced collapse, fragmentation, and surface irregularities, in contrast to the smooth, intact morphology observed in untreated controls.

These structural disruptions confirm that plasma inflicts mechanical damage on fungal cells, likely due to etching effects and cell wall weakening caused by reactive plasma species. These observations reinforce the hypothesis that plasma treatment exerts its antifungal activity through both biochemical (oxidative) and physical mechanisms.

AFM findings also suggest that even fungi exhibiting biochemical resilience to plasma exposure (e.g., *Geotrichum candidum*) are still susceptible to mechanical damage, underscoring the multi-target nature of plasma action.

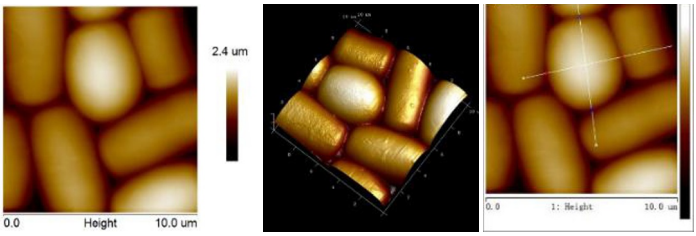

Fig. 5. Atomic force microscopy images of *Geotrichum candidum* (CK): height map, 3D topography, and length-width profile.

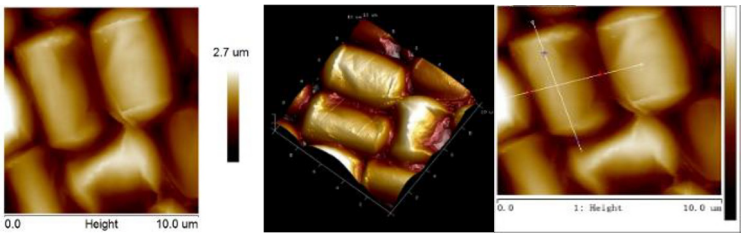

Fig. 6. Atomic force microscopy images of *Geotrichum candidum* after 7-minute plasma treatment: height map, 3D topography, and length-width profile.

This study systematically evaluated the effects of 150 W cold plasma treatment on postharvest strawberries, with particular focus on fungal suppression, fruit quality, and pesticide residue degradation. Although this study verified the complete degradation effect of the pesticide under 150 W low-temperature plasma treatment, the selection of only one pesticide type limited the generalization ability of the research conclusions to a certain extent. In actual production, common pesticide residues on the surface of strawberries also include dichlorvos, cypermethrin and carbendazim.

5 Conclusion

This study confirms that 150 W cold plasma treatment, particularly at a 7-minute duration, is an effective postharvest intervention for strawberries. Key findings include: A 2-day extension of shelf life under ambient conditions ($p < 0.05$). Significant inhibition of fungal hyphal growth through oxidative stress and structural disruption ($p < 0.05$).

These outcomes demonstrate that cold plasma is a dual-function preservation technology—simultaneously improving microbial safety and reducing chemical hazards. Future work should investigate the scalability of plasma treatment and its integration into commercial postharvest handling systems, accounting for variables as fruit load, humidity, and plasma uniformity.

It is worth noting that despite the excellent experimental results under laboratory control conditions, the large-scale promotion of plasma treatment in actual cold chain systems still faces several engineering and technical challenges. How to maintain the uniformity of the reaction gas and the power density of the plasma in the process of expanding the processing scale to batch-level fruits is a key issue affecting stability of treatment effect.

References

1. Song, Y., Wang, Z., Jing, Q., & others. (2025). Research progress on strawberry harvest, storage, and processing technologies. Northern Horticulture, (05), 115–122.
2. Yan, G., Zhao, Y., Shi, J., & others. (2018). Study on postharvest physiological characteristics and storage traits of different strawberry cultivars. Preservation and Processing, 18(4), 34–38.
3. Jiang, L., Tianaka, K., Lu, X., & others. (2021). Analysis of pesticide registration status for strawberries in China. Journal of Biological Disaster Science, 44(2), 159–162.
4. Wang, J., Zhao, W., Ma, M., & others. (2021). Advances in strawberry postharvest physiological changes and preservation technologies. Anhui Agricultural Sciences, 49(6), 39–42.
5. Ali, M., Cheng, J. H., & Sun, D. W. (2021). Effects of dielectric barrier discharge cold plasma treatments on degradation of anilazine fungicide and quality of tomato (Lycopersicon esculentum Mill) juice. International Journal of Food Science & Technology, 56(1), 69–75.
6. Zhao, Y., Yan, L., Yan, W., & Zhang, J. (2022). Effect of combined cold plasma-activated water and dielectric barrier discharge treatment on sterilization efficacy and quality of strawberries. Food Science, 43(17), 105–116.
7. Zhang, W., Cao, X., & Xing, Y. (2018). Determination of strawberry fruit hardness using a texture analyzer. Bio-101, e1010218.
8. Ma, W., Zhang, Y., Wang, C., Liu, T., Pu, X., Ma, Z., Gao, S., & Sun, Y. (2018). A new disease of strawberry, fruit rot, caused by *Geotrichum candidum* in China. Plant Protection Science, 54(2), 92–100.
9. Fu, J., Wu, X., Zhang, C., Liu, Q., Zhou, Y., & Lin, X. (2024). Genomic analysis of *Talaromyces verruculosus* SJ9: An efficient tetracycline-, enrofloxacin-, and tylosin-degrading fungus. Genes, 15(12), 1643.
10. Li, Y., Li, C., Zhang, X., & others. (2024). Study on the effect of plasma gas treatments on strawberry preservation. Journal of Beijing Institute of Graphic Communication, 32(12), 17–22.
11. Wang, S., Meng, J., Zhang, Y., & others. (2009). Effect of plasma on degradation of dimethoate in apple and Chinese cabbage. Transactions of the Chinese Society of Agricultural Engineering, 25(12), 318–323.