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Effectiveness of Low-Cost Ozone Treatment in Preserving the Postharvest Quality of Chilli Pepper under Tropical Ambient Storage

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ABSTRACT

Postharvest losses of red chilli peppers remain a significant challenge in tropical regions, particularly under ambient storage conditions where access to refrigeration is limited. This study evaluates the effectiveness of simple ozonation at different exposure durations in maintaining the quality of red chilli peppers and identifies the optimal treatment duration based on quality preservation performance. A controlled experimental design with four treatments, consisting of no ozone exposure and ozonation for 5, 10, and 15 min, was applied. Quality parameters included weight retention, firmness, vitamin C content, water content, and microbial load were observed during ten days of storage. The results showed that ozonation significantly affected all measured parameters, with longer exposure durations generally improving quality retention and reducing microbial growth. However, the 10-min treatment demonstrated comparable performance to that of 15-min treatment across most variables, indicating that an optimal exposure duration had been reached. These findings suggest that simple ozonation can serve as a practical and effective postharvest approach for maintaining red chilli quality under tropical ambient conditions, particularly for small-scale applications.

1. INTRODUCTION

Red chilli (*Capsicum annuum* L.) is an important horticultural commodity in tropical regions due to its high economic value, strong market demand, and its contribution to food security and farmer livelihoods. However, red chilli is highly perishable, particularly under ambient storage conditions, due to its high respiration rate, rapid transpiration, tissue softening, and susceptibility to microbial spoilage. Postharvest losses remain a major challenge, especially in tropical environments where access to refrigeration is limited. Previous studies have reported that losses can reach 28.6% during the dry season and 38.7% during the rainy season under tropical conditions (Tiamiyu *et al*., 2023). In addition, storage at room temperature (25–30 °C) has been associated with rapid quality deterioration and increased microbial growth (Kapur *et al*., 2022). These challenges highlight the need for effective and practical postharvest technologies suitable for tropical supply chains.

Various postharvest technologies have been developed to extend the shelf life of horticultural commodities. Refrigeration and controlled atmosphere storage can reduce respiration rates and maintain physiological stability, while edible coatings have been shown to reduce moisture loss and preserve fruit quality (Abdullah & Abou-Elwafa, 2023; Zare-Bavani *et al*., 2024). However, these technologies often require high investment, energy input, and specialised infrastructure, limiting their applicability for smallholder farmers in developing countries (Tiamiyu *et al*., 2023). As a result, there is a growing need for alternative technologies that are simple, cost-effective, and suitable for use under ambient tropical conditions.

Ozonation has emerged as a promising nonthermal postharvest technology due to its strong oxidative properties. Previous studies have reported that ozone treatment can reduce microbial growth and help maintain product quality in horticultural commodities such as strawberries, peppers, and tomatoes (Botondi *et al*., 2021; Zare-Bavani *et al*., 2024). Ozone exposure has also been associated with improvements in physical and chemical quality parameters, including moisture retention and antioxidant stability. However, most of these studies have been conducted under controlled or refrigerated conditions, which limits their direct applicability to real-world tropical storage systems.

Despite the growing interest in ozone-based preservation, several research gaps remain. First, studies investigating ozonation under tropical ambient conditions without refrigeration are still limited (da Silva Neto *et al*., 2019). Second, the application of low-capacity ozone generators, which are more accessible for smallholder farmers, has received relatively little attention (Chankuson & Chumsri, 2023). Third, many existing studies focus on a limited number of quality parameters, resulting in an incomplete understanding of the combined physiological, chemical, and microbiological responses during storage (Enríquez-Castro *et al*., 2021; Ullrich *et al*., 2023; Zhang *et al*., 2020). In addition, ozonation durations used in previous studies are often optimised for controlled environments and may not be suitable for practical implementation in tropical supply chains (Sarron *et al*., 2021).

Therefore, there is a need for a more integrated and context-relevant evaluation of ozonation that reflects real storage conditions faced by smallholder farmers. A comprehensive assessment that includes weight retention, firmness, water content, vitamin C content, and microbial load is essential to better understand the multidimensional effects of ozone treatment. Furthermore, incorporating a comparative analysis of treatment effectiveness is important to ensure that the proposed technology is not only scientifically valid but also practically applicable.

This study aims to evaluate the effectiveness of simple ozonation using a low-capacity ozone generator at different exposure durations in maintaining the postharvest quality of red chilli peppers under tropical ambient conditions, and to identify the optimal treatment duration based on quality preservation performance. The outcomes of this research are expected to provide a scientific basis for developing simple, effective, and applicable postharvest technologies for horticultural commodities in tropical regions.

2. MATERIALS AND METHODS

2.1. Research Design

This study employed a controlled quantitative experimental design consisting of four treatments: no ozone exposure (control), and ozonation for 5, 10, and 15 min. Ozonation was carried out using a portable ozone generator (Oxitech Home Series, 300–500 mg O_3/h capacity) within a chamber of 30–50 L. Samples were stored for 10 days under ambient tropical conditions to simulate typical postharvest storage. Data were analysed using one-way analysis of variance (ANOVA) followed by Tukey HSD post hoc test ($\alpha = 0.05$), after confirming normality using the Shapiro–Wilk test and homogeneity of variance using Levene's test. Effect size (η^2) was calculated to determine the magnitude of treatment effects, where values of 0.01, 0.06, and 0.14 represent small, medium, and large effects, respectively. To ensure safety, ozone exposure was maintained below 0.1 ppm in accordance with OSHA and NIOSH guidelines, supported by adequate ventilation and the use of protective equipment.

2.2. Location, Tools, and Research Samples

The study was conducted in a simple ozonation chamber and a storage room maintained at 25–28 °C and 70–80% relative humidity. Fresh red chillies were obtained from a local traditional market in Rejang Lebong Regency, Indonesia, on the day of the experiment to ensure freshness and uniformity. The samples were selected purposively based on uniform size, ripeness, and physical condition, and damaged fruits were excluded. Ozonation was performed using a portable ozone generator (Oxitech Home Series, 300–500 mg O_3/h capacity) placed within a 30–50 L chamber, for which ozone distribution had been previously validated. Weight measurements were conducted using a digital analytical balance (AND EK-600i, Japan). Firmness was measured using a digital penetrometer (Model FT-327, QA Supplies, USA). Other laboratory equipment included a drying oven, incubator, and standard microbiological tools used for total plate count analysis. A total of 40 chilli samples were used, with 10 fruits assigned to each treatment group. This sample size was considered adequate for statistical analysis using ANOVA in small-scale postharvest experiments.

2.3. Data Collection Techniques

The quality parameters observed in this study included weight retention, firmness, vitamin C content, water content, microbial load, and treatment cost. Weight retention (%) was determined by measuring sample weight using a digital analytical balance (AND EK-600i, Japan) with a precision of 0.01 g on days 0, 2, 4, 6, 8, and 10. Weight loss (%) was calculated as ((Initial weight − Final weight) / Initial weight) × 100, and weight retention (%) was subsequently calculated as 100 − weight loss (%). Firmness was measured using a digital penetrometer (Model FT-327, QA Supplies, USA) equipped with an 8 mm probe and expressed in Newton (N). Vitamin C content was analysed using the iodimetric titration method and expressed as mg/100 g of fresh weight, with measurements conducted on days 0 and 10. Water content (%) was determined using the oven drying method at 105 °C until constant weight was achieved. Surface microbial load was assessed using the Total Plate Count (TPC) method on Nutrient Agar following incubation at 37 °C for 48 hours, and the results were expressed as log CFU/g. Treatment cost (USD/kg) was estimated based on electrical energy consumption, treatment duration, and equipment depreciation using the equation $Cost = (E \times T \times C_e + D) / W$, where E represents electrical power consumption (kW), T is treatment time (hours), C_e is the electricity tariff (USD/kWh), D is depreciation cost (USD), and W is sample weight (kg). All measurements were conducted under consistent environmental conditions to ensure comparability across treatments.

2.4. Research Procedures

The samples were first sorted and selected based on uniform size, ripeness, and physical condition, and then cleaned without washing to avoid excess moisture. The samples were subsequently placed into an ozonation chamber that had reached stable operating conditions prior to treatment. Ozonation was applied for 5, 10, and 15 minutes according to the designated treatments, while the control group (P0) received no ozone exposure. After treatment, all samples were stored on an open shelf under ambient tropical conditions until day 10. Measurements of all quality parameters were conducted according to the predefined observation schedule. All treatments were conducted under the same environmental conditions to ensure comparability. Occupational safety measures were implemented throughout the experiment, including maintaining adequate ventilation, ensuring ozone concentration remained below 0.1 ppm, and the use of activated carbon masks and protective gloves.

2.5. Data Analysis Techniques

All data were analysed using one-way analysis of variance (ANOVA) to evaluate the effect of ozonation treatments on the observed parameters. Prior to analysis, data normality was assessed using the Shapiro–Wilk test and homogeneity of variance was evaluated using Levene's test. Differences among treatment means were further analysed using Tukey HSD post hoc test at a significance level of 0.05. Effect size (η^2) was calculated to determine the magnitude of treatment effects. Graphical analysis was performed to illustrate trends in weight retention, firmness, vitamin C, water content, and microbial load during storage. A comparative analysis of treatment effectiveness was conducted by relating treatment duration to quality preservation performance. All statistical analyses were performed using IBM SPSS Statistics.

3. RESULTS AND DISCUSSION

3.1. Summary of ANOVA Results Tukey HSD Test

This section presents the statistical findings for all quality parameters of red chilli subjected to different ozonation durations. ANOVA was employed to determine whether significant differences existed among treatments, followed by Tukey's HSD test to identify specific treatment groups exhibiting statistically significant variation. A summary of the analytical results is provided in Table 1.

Analysis of variance (ANOVA) demonstrated that all observed quality parameters of red chilli peppers were significantly affected by ozonation treatments ($p < 0.05$). Tukey HSD post hoc analysis further confirmed statistically significant differences among treatment groups for all measured variables. Increasing ozonation duration improved quality preservation across all parameters. Weight retention increased progressively from 80.80% in the control treatment to 89.00% in the 15-min treatment, indicating reduced mass loss during storage. Similarly, firmness was better maintained in ozonated samples, with the highest values observed in the 10- and 15-min treatments. Vitamin C content

Table 1. ANOVA statistical analysis and Tukey HSD advanced test on red chilli quality parameters after ozonation treatment

Quality Variables	Ozonation Treatment	Mean ± SD	Tukey's notation (α = 0.05)	*F* Value	Sig. (*p*)	Information
Weight Retention (%)	P0 (Control)	80.80 ± 1.85	a	31.27	0.000	Significantly different between treatments
	P1 (5 min)	84.60 ± 1.50	b			
	P2 (10 min)	87.90 ± 1.20	c			
	P3 (15 min)	89.00 ± 1.00	c			
Firmness (N)	P0 (Control)	4.20 ± 0.50	a	24.16	0.000	Significantly different between treatments
	P1 (5 min)	5.45 ± 0.35	b			
	P2 (10 min)	6.20 ± 0.25	c			
	P3 (15 min)	6.40 ± 0.20	c			
Vitamin C (mg/100 g)	P0 (Control)	95.40 ± 4.20	a	18.42	0.000	Significantly different between treatments
	P1 (5 min)	115.60 ± 3.80	b			
	P2 (10 min)	128.50 ± 2.90	c			
	P3 (15 min)	131.00 ± 2.50	c			
Water Content (%)	P0 (Control)	83.20 ± 0.70	a	22.88	0.000	Significantly different between treatments
	P1 (5 min)	84.50 ± 0.60	b			
	P2 (10 min)	85.80 ± 0.50	c			
	P3 (15 min)	86.10 ± 0.40	c			
Microbial Count (log CFU/g)	P0 (Control)	4.68 ± 0.15	a	27.55	0.000	Significantly different between treatments
	P1 (5 min)	4.41 ± 0.12	b			
	P2 (10 min)	4.08 ± 0.10	c			
	P3 (15 min)	3.93 ± 0.09	c			

and water content also showed improved retention with longer ozonation durations, while microbial counts were significantly reduced, particularly in treatments P2 and P3.

The similarity of Tukey groupings between the 10- and 15-minute treatments across multiple parameters suggests that an optimal ozonation duration may have been reached. Beyond this point, additional exposure time did not result in statistically significant improvements, indicating a threshold response. This pattern reflects a dose–response relationship in which ozonation enhances quality retention up to an optimal level.

From a physiological perspective, the improved weight retention observed in ozonated samples may be associated with reduced transpiration and respiration rates during storage. Weight changes in fresh produce are primarily governed by moisture loss and metabolic activity rather than tissue softening processes. Therefore, the observed differences are more likely related to changes in surface permeability and physiological activity. The preservation of firmness in ozonated treatments may be linked to delayed degradation of cell wall structure. Fruit softening is generally associated with enzymatic breakdown of structural components, and previous studies have suggested that ozone exposure may help slow these processes. However, enzymatic activity was not directly measured in this study, and this explanation is inferred from existing literature.

Higher vitamin C retention in ozonated samples may be attributed to reduced oxidative degradation during storage. Ascorbic acid is sensitive to oxidation, and its stability is influenced by environmental and metabolic conditions. Previous studies have reported that ozone treatment may contribute to maintaining antioxidant stability in horticultural commodities. Improved water content retention in treatments P2 and P3 further indicates that ozonation may help maintain tissue integrity and reduce moisture loss. Water loss is primarily influenced by cuticle permeability and environmental gradients, and ozone exposure has been reported to modify surface characteristics that reduce transpiration. The substantial reduction in microbial counts observed in ozonated samples confirms the antimicrobial effect of ozone. As a strong oxidising agent, ozone can damage microbial cell membranes and reduce cell viability. This finding is consistent with previous studies reporting the effectiveness of ozone in suppressing microbial growth on fresh produce (Chitravathi *et al*., 2015; Glowacz & Rees, 2016; Putri *et al*., 2024; Sasmita *et al*., 2018).

Overall, these findings demonstrate that ozonation duration plays a critical role in determining treatment effectiveness. The 10- and 15-min treatments showed comparable performance across most parameters, suggesting that extending exposure beyond a certain duration does not provide substantial additional benefits. Therefore, optimisation of ozonation duration is essential to achieve effective and practical quality preservation under tropical ambient storage conditions.

3.2. Weight Retention (%)

Figure 1 illustrates the pattern of Weight Retention (%) in red chillies over ten days of storage under different ozonation treatment durations. Observations over ten days of storage showed that ozonation treatments significantly improved weight retention in red chillies compared with the untreated control ($p < 0.05$). The control treatment exhibited the lowest retention value (80.80%), indicating greater mass loss during storage. In contrast, ozonated samples maintained higher retention values, reaching 84.60% for the 5-min treatment and 87.90–89.00% for the 10- and 15-min treatments. This pattern demonstrates a clear dose–response relationship, in which longer ozonation durations were associated with improved weight preservation and greater stability during storage. The higher weight retention observed in ozonated samples may be associated with reduced transpiration and respiration rates. Weight loss in fresh produce is primarily driven by moisture diffusion and metabolic activity rather than tissue softening processes. Therefore, the improved retention observed in this study is more likely related to changes in surface permeability and physiological activity rather than enzymatic softening mechanisms.

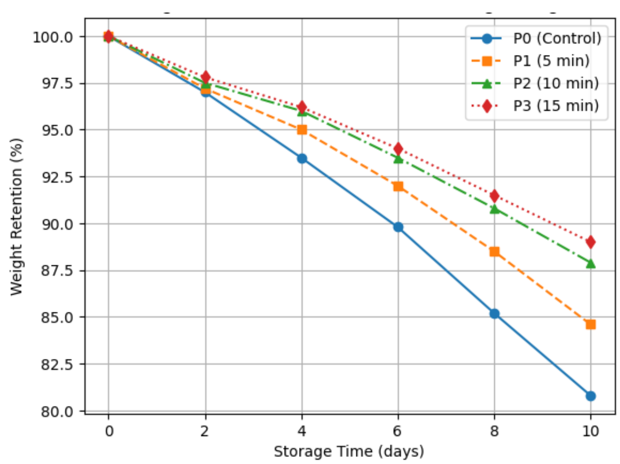

Figure 1. Weight retention (%) of red chilli during storage at different ozonation durations. Higher values indicate better preservation of initial weight.

Previous studies have reported that ozone treatment can inhibit microbial growth, reduce water loss, and maintain cellular structure in red chillies during storage (Putri *et al*., 2024; Sasmita *et al*., 2018). The effectiveness of ozone has also been associated with improved oxidative stability and reduced deterioration processes, which may contribute to prolonged freshness (Sachadyn-Król *et al*., 2019). In addition, postharvest physiology principles indicate that water loss is influenced by cuticle permeability, epidermal integrity, and fruit respiratory activity, all of which may be affected by ozone exposure. The progressive increase in weight retention from 5 to 15 min further supports the presence of a dose–response relationship. The 15-min treatment exhibited the highest retention, indicating maximum preservation of fruit mass during storage. However, the 10-min treatment showed comparable results, suggesting that an optimal duration may have been reached, beyond which additional exposure provides limited benefit. This observation is consistent with previous findings indicating that ozone can function as both an antimicrobial agent and a regulator of postharvest physiological processes (Kusumiyati *et al*., 2022). Furthermore, field-based studies have reported that ozone treatment, when combined with appropriate handling and distribution practices, can substantially reduce postharvest losses in tropical chilli supply chains (Munarso *et al.*, 2020).

These results are also consistent with studies on other horticultural commodities. For example, ozone has been reported to reduce transpiration by modifying the cuticle layer and stabilising epidermal structure in bell peppers (Holden *et al*., 2023). Cuticle thickness and exocarp lipid composition in *Capsicum annuum* are known to play important roles in moisture retention and postharvest quality. Similar effects have been observed in cayenne pepper, where ozone treatment helped preserve epidermal integrity and reduce oxidative stress (Alsahli *et al*., 2020). Collectively, these findings indicate that ozone-based preservation mechanisms are applicable across different commodities and support the potential of low-capacity ozonation as a practical postharvest technology for tropical conditions.

3.3. Firmness of Red Chilli Fruit (N)

Figure 2 illustrates the changes in firmness (N) of red chillies over ten days of storage under different ozonation treatment durations. Firmness of red chilli peppers decreased during storage across all treatments but was significantly better preserved in ozonated samples ($p < 0.05$). The control treatment showed the lowest final firmness (4.20 N), indicating substantial softening from the initial value (8.20 N). In contrast, the 5-min ozonation treatment retained a firmness of 5.45 N, while the 10- and 15-min treatments maintained higher values ranging from 6.20 to 6.40 N. These results indicate that increasing ozonation duration effectively delayed tissue softening and improved texture preservation during storage.

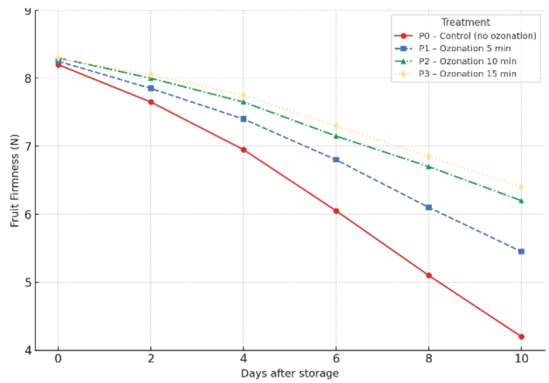

Figure 2. Firmness of red chilli fruit (N) during storage at various ozonation durations

The improved firmness observed in ozonated samples may be associated with reduced degradation of cell wall structure. Fruit softening is primarily related to the breakdown of structural polysaccharides in the cell wall, which leads to loss of tissue integrity and mechanical strength. Previous studies have suggested that ozone exposure may influence these processes by slowing structural degradation and maintaining cellular integrity during storage.

Biochemically, softening is commonly associated with the activity of enzymes such as polygalacturonase (PG) and pectin methylesterase (PME), which contribute to pectin degradation in the middle lamella. In addition, cellulases are involved in the breakdown of cellulose and hemicellulose components of the cell wall. Some studies have reported that mild oxidative treatments, including ozone, may reduce the activity of these enzymes and thereby delay softening. However, it is important to emphasise that enzymatic activity was not directly measured in this study. Therefore, these mechanisms are inferred from previous literature rather than experimentally verified in the present work.

The findings of this study are consistent with those of He *et al*. (2025), who reported that the polygalacturonase (PG) gene plays a central role in cell wall degradation in *Capsicum annuum* and that its activity may be moderated through mild oxidative treatments such as ozone. Additional studies have shown that ozone treatment can suppress microbial growth, reduce moisture loss, and extend the shelf life of red chilli peppers (Putri *et al*., 2024). Similar results have been reported in paprika, where ozonation combined with modified atmospheres helped maintain firmness and prolong shelf life (Hamed *et al*., 2021; Yeboah *et al*., 2023).

Overall, the results demonstrate that ozonation contributes to maintaining fruit firmness by slowing tissue degradation processes during storage. The comparable performance observed in the 10- and 15-min treatments suggests that an optimal exposure duration may exist, beyond which additional treatment provides limited benefit. These findings highlight the importance of optimising ozonation duration to achieve effective texture preservation in red chilli peppers under tropical storage conditions.

3.4. Vitamin C Content (mg/100g) of Red Chillies

Figure 3 visualize the changes in vitamin C content (mg per 100 g) of red chillies during storage under different ozonation treatment durations. Vitamin C content differed significantly among treatments ($p < 0.05$). The control treatment showed the lowest value at the end of storage (95.40 mg/100 g), whereas ozonated samples maintained higher levels, reaching 115.60 mg/100 g in the 5-min treatment and 128.50–131.00 mg/100 g in the 10- and 15-min treatments. These results indicate that ozonation contributed to preserving ascorbic acid during storage, with longer exposure durations associated with greater retention. The higher vitamin C retention observed in ozonated samples may be associated with reduced oxidative degradation during storage. Ascorbic acid is highly sensitive to oxidation, and its stability is influenced by oxygen exposure, enzymatic activity, and overall metabolic processes. Ozone treatment, when applied at appropriate levels, has been reported to influence oxidative balance and may help maintain antioxidant stability in horticultural commodities.

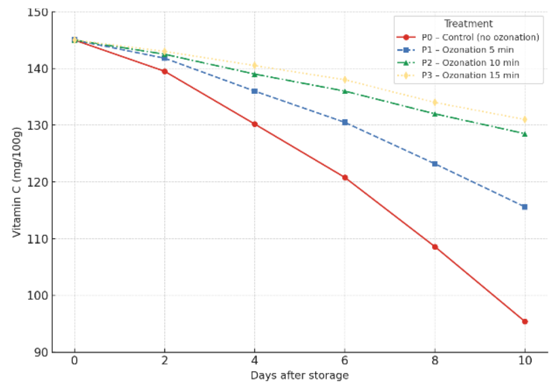

Figure 3. Vitamin C content (mg/100 g) of red chillies during storage at various ozonation durations

Previous studies have shown that low-dose ozone treatment can contribute to maintaining ascorbate levels by influencing cellular redox conditions. For example, ozone treatment has been reported to help preserve vitamin C in strawberries by regulating oxidative processes (Zhang *et al*., 2020). In addition, ozone exposure has been associated with enhanced antioxidant enzyme activity and delayed ascorbic acid degradation during storage (Zhang *et al*., 2020). In bell peppers, key regulatory mechanisms involved in ascorbic acid biosynthesis have been identified and may be influenced by mild oxidative treatments (Fenech *et al*., 2019; Rodríguez-Ruiz *et al*., 2017). Furthermore, ozone-based postharvest technology has been shown to maintain vitamin C levels and extend shelf life without compromising product quality (Yeboah *et al*., 2023). However, it is important to emphasise that the biochemical pathways involved in vitamin C stabilisation were not directly measured in this study. Therefore, the proposed mechanisms are inferred from previous literature rather than experimentally verified in the present work. Overall, the results suggest that ozonation can contribute to maintaining vitamin C content by reducing degradation processes during storage. The similar performance observed in the 10- and 15-min treatments indicates that an optimal ozonation duration may exist, beyond which additional exposure provides limited additional benefit.

3.5. Water Content of Red Chilli Peppers (*Capsicum annuum* L.)

The changes in water content of red chillies before and after storage under different ozonation treatment durations was visualized in Figure 4. Water content decreased during storage across all treatments but showed significant differences among ozonation durations ($p < 0.05$). The control treatment exhibited the greatest reduction (4.80%), whereas the 5-min ozonation treatment showed a decrease of 3.50%. The smallest reductions were observed in the 10- and 15-min treatments, ranging from 2.20% to 1.90%. These results indicate that longer ozonation durations contributed to improved moisture retention during storage. The improved water retention observed in ozonated samples may be associated with the maintenance of surface integrity and reduced transpiration rates. Water loss in fresh produce is primarily governed by cuticle permeability, epidermal structure, and the moisture gradient between the tissue and its surrounding environment. Previous studies have reported that ozone exposure may induce mild structural modifications on the fruit surface, which can reduce water vapour diffusion and improve moisture retention (Botondi *et al*., 2021; Piechowiak *et al*., 2022).

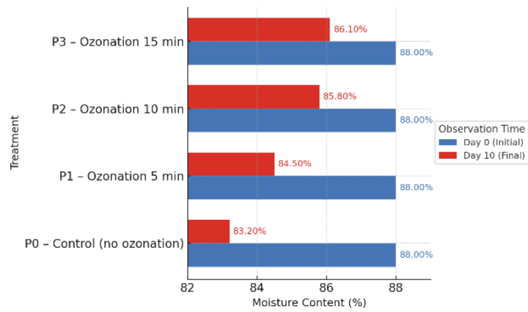

Figure 4. Water content (%) of red chilli fruit at various ozonation treatment durations before and after storage

In addition, cuticle thickness and surface composition play important roles in determining resistance to water loss. For example, cuticle development has been directly linked to water loss rates in chilli peppers (Konishi *et al*., 2021), while the lipid composition of the exocarp contributes to postharvest stability in *Capsicum annuum* (Holden *et al*., 2023). Epidermal characteristics, including cell density and cuticle thickness, also influence resistance to moisture loss (Marinov *et al*., 2023). Furthermore, specific cuticular components such as n-alkanes have been shown to reduce water vapour diffusion and extend shelf life (Parsons *et al*., 2013). Modifications to surface structure have also been associated with reduced transpiration and improved storage performance in bell peppers (Díaz-Pérez *et al*., 2020). However, it is important to emphasise that these structural and physiological mechanisms were not directly measured in this study. The explanations provided are inferred from previous literature rather than experimentally verified in the present work.

Overall, the findings demonstrate that ozonation can contribute to maintaining water content by reducing moisture loss during storage. The similar performance observed in the 10- and 15-minute treatments suggests that an optimal ozonation duration may exist, beyond which additional exposure provides limited additional benefit. These results highlight the importance of optimising ozonation duration to improve postharvest moisture retention under tropical ambient conditions.

3.6. Surface Microbial Count (CFU/g) of Red Chilli Peppers

Figure 5 presents the changes in surface microbial counts (CFU per gram) of red chillies before and after storage under different ozonation treatment durations. Surface microbial counts increased during storage across all treatments but showed significant differences among ozonation durations ($p < 0.05$). The control group exhibited the highest increase in microbial load, approximately forty-fold, whereas the 5-min ozonation treatment showed a lower increase of approximately twenty-two-fold. The 10- and 15-min treatments displayed substantially smaller increases, approximately ten-fold and seven-fold, respectively. These results indicate that longer ozonation durations were associated with more effective suppression of microbial growth on the surface of red chilli peppers. The reduction in microbial load observed

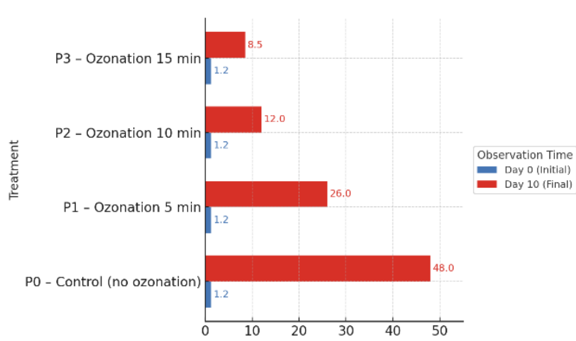

Figure 5. Surface microbial count (CFU/g) of red chilli peppers at various ozonation durations before and after storage

in ozonated samples is consistent with the known antimicrobial properties of ozone. Ozone is a strong oxidising agent that can interact with microbial cell components, including membrane lipids and proteins, leading to structural damage and reduced cell viability. Previous studies have reported that ozone exposure can disrupt microbial cell membranes and inhibit microbial proliferation on fresh produce (Glowacz & Rees, 2016; Nayak *et al*., 2019).

At the molecular level, ozone has been reported to induce oxidative reactions that may lead to lipid peroxidation, increased membrane permeability, and disruption of cellular functions (Bernal *et al*., 2024). In addition, ozone exposure has been associated with the inactivation of key metabolic processes in microorganisms, including respiratory pathways (Glowacz & Rees, 2016). Similar effects have been observed in various horticultural commodities, where ozonation reduced microbial growth and extended shelf life (Nayak *et al*., 2019; Onopiuk *et al*., 2021). However, it is important to emphasise that these molecular mechanisms were not directly examined in this study. Therefore, the explanations provided are based on previously reported findings and should be interpreted as supportive rather than experimentally verified mechanisms. Overall, the findings demonstrate that ozonation effectively reduces microbial proliferation during storage, with longer exposure durations resulting in greater suppression. The comparable performance observed in the 10- and 15-minute treatments suggests that an optimal ozonation duration may exist, beyond which additional exposure provides limited additional benefit. These results highlight the importance of optimising ozonation duration to achieve effective microbial control under tropical postharvest conditions.

3.7. Comparative Effectiveness of Ozonation Duration

Table 2 compares the cost of ozonation treatments with their effectiveness in reducing yield losses, thereby illustrating the economic efficiency of each exposure duration. The comparison of ozonation duration and quality preservation performance indicates that the 10-min treatment provided a favourable balance between treatment duration and effectiveness. This treatment reduced yield loss by approximately 37% at an estimated cost of 0.0041 USD/kg, while the 5-min treatment resulted in a lower reduction of approximately 20% at 0.0028 USD/kg. The 15-min treatment achieved a higher reduction of approximately 43% but required a higher cost of 0.0053 USD/kg. These results suggest that increasing ozonation duration improved treatment effectiveness; however, the magnitude of improvement between 10 and 15 min was relatively small compared to the additional input required.

This pattern indicates that extending ozonation duration beyond a certain point may result in diminishing practical gains, where additional treatment time provides limited incremental benefit. Similar observations have been reported in previous studies, where optimised ozone exposure improved product quality without proportionally increasing operational inputs (Zardzewiały *et al*., 2024). In addition, longer ozonation durations have been associated with increased energy use and processing time without substantial additional benefits (Onopiuk *et al*., 2021). The importance of balancing treatment efficiency and resource use has also been highlighted in postharvest systems for horticultural commodities, where sustainable technologies are expected to preserve product quality while minimizing energy consumption, processing costs, and environmental impacts (Jarman *et al*., 2023; Rizzo, 2025).

The findings of this study suggest that the 10-minute ozonation duration may represent a practical option for application, particularly in small-scale or resource-limited settings. This duration provided substantial improvements in quality parameters while maintaining relatively moderate treatment requirements. However, it is important to emphasise that the economic evaluation presented in this study is based on simplified estimations of treatment cost and yield loss reduction. Detailed economic analyses, including scale effects, operational variability, and long-term cost implications, were not comprehensively assessed. Therefore, conclusions related to cost efficiency and economic optimisation should be interpreted with caution. Overall, the results highlight the importance of optimising ozonation duration to achieve an effective balance between treatment performance and practical applicability under tropical postharvest conditions.

Table 2. Comparison of cost efficiency and effectiveness of ozonation treatment on yield loss reduction

Treatment	Cost (USD/kg)	Yield Loss Reduction (%)	Economic Value
Control (without ozone)	0.000	0	Inefficient, high losses
Ozone 5 min	0.0028	~20%	Quite efficient
Ozone 10 min	0.0041	~37%	Most efficient
Ozone 15 min	0.0053	~43%	Effective but higher cost

3.8. General Discussion

The integration of the research findings demonstrates that simple ozonation influences the quality of red chilli peppers through interconnected physiological and microbiological processes during storage. Ozonation for 10 to 15 minutes was associated with improved quality retention, including higher weight retention, better firmness, greater vitamin C stability, improved water content, and reduced microbial load. These effects may be related to changes in transpiration and respiration rates, maintenance of tissue integrity, and suppression of microbial proliferation. From a physiological perspective, the observed improvements in weight retention and water content may be associated with reduced moisture loss, which is primarily governed by cuticle permeability, epidermal structure, and environmental gradients. Similarly, the preservation of firmness may be linked to slower degradation of cell wall components during storage. In addition, the higher vitamin C retention observed in ozonated samples may be associated with reduced oxidative degradation under storage conditions. However, it is important to emphasise that these physiological and biochemical mechanisms were not directly measured in this study and are therefore interpreted based on previously reported findings.

The reduction in microbial load observed in ozonated treatments is consistent with the known antimicrobial properties of ozone. As a strong oxidising agent, ozone has been reported to interact with microbial cell components, leading to structural disruption and reduced viability. These antimicrobial effects contribute to improved postharvest quality and extended shelf life under ambient storage conditions. When considered within the broader research context, this study addresses an important gap related to the application of simple, low-capacity ozonation systems under tropical, nonrefrigerated conditions. Most previous studies have focused on high-capacity industrial systems operating under controlled environments. For example, ozone treatment has been evaluated in refrigerated storage systems for tomatoes, showing significant effects on chemical and microbiological parameters (Onopiuk *et al*., 2021). In addition, field-level studies have demonstrated that low-dose ozone applications can influence fruit quality attributes, including vitamin C content and structural stability (Zardzewiały *et al*., 2024).

The findings of this study extend previous research by demonstrating that comparable trends in quality preservation can be achieved using simple ozonation systems, provided that exposure duration is appropriately optimised. In particular, the similar performance observed between the 10- and 15-min treatments across multiple parameters suggests that an optimal exposure duration may exist, beyond which additional treatment provides limited additional benefit. Overall, these results highlight the potential of simple ozonation as a practical postharvest approach for maintaining the quality of red chilli peppers under tropical ambient conditions, while emphasising the importance of optimising treatment duration to achieve effective and efficient outcomes.

4. CONCLUSIONS

This study demonstrates that simple ozonation can effectively maintain the postharvest quality of red chilli peppers under tropical ambient storage conditions. Ozonation treatments significantly improved weight retention, firmness, vitamin C content, and water content, while reducing microbial load compared with the untreated control. These findings indicate that ozonation contributes to slowing quality deterioration during storage. Among the tested treatments, the 10- and 15-min ozonation durations showed comparable performance across most quality parameters, suggesting that an optimal exposure duration may exist. While the 15-min treatment provided slightly higher preservation in some variables, the additional improvement was relatively small compared to the increased treatment time.

The results highlight that simple, low-capacity ozonation can serve as a practical postharvest approach, particularly for small-scale applications in tropical regions where access to advanced storage technologies is limited. However, it should be noted that the underlying physiological and biochemical mechanisms were not directly measured in this study, and the explanations provided are based on previously reported findings. Future research is recommended to investigate the detailed mechanisms of ozone interaction with plant tissues and to evaluate long-term application under real supply chain conditions. Further studies incorporating broader economic and operational analyses are also needed to strengthen the applicability of ozone-based postharvest technologies.

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AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
IMS	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
KNS	✓	✓		✓	✓	✓	✓	✓		✓				
AP	✓	✓		✓	✓		✓			✓		✓		
PA	✓			✓			✓			✓	✓	✓	✓	

C: Conceptualization	Fo: Formal Analysis	O: Writing – Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing – Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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