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Enhancing shelf life and quality attributes of fresh in-hull pistachio by cold plasma treatment during cold storage

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ABSTRACT

Purpose: This study evaluated the effects of cold plasma (CP) treatment using argon (Ar), nitrogen (N_2), and oxygen (O_2) gases at two voltages (5 and 8 kV) on the postharvest quality and shelf life of fresh in-hull pistachio (*Pistacia vera* L.) during cold storage. **Research Method:** Treatments were applied, and the samples were stored at 4°C for 25 and 50 days. Key parameters, including decay index (DI), water activity, total phenolic content (TPC), total flavonoid content (TFC), total chlorophyll content, electrolyte leakage (EL), and sensory attributes, were assessed. **Findings:** Decay index (DI) measurements demonstrated that CP treatments significantly inhibited microbial spoilage, and argon-CP reduced decay by up to 40% compared to untreated controls. Water activity declined from 0.957 in the controls to as low as 0.952 in the argon-treated samples, indicating reduced free water available for microbial growth. Biochemical analyses revealed that total phenolic content (TPC) increased the most under nitrogen-CP (0.485 mg GAE/100 g at 50 days vs. 0.350 mg in controls). Total chlorophyll content was highest in N_2-treated pistachios (2.96 g kg^{-1}), and electrolyte leakage (EL), an indicator of membrane integrity, was lowest in argon-CP samples (74.82% vs. 88.67% in controls), reflecting reduced cellular damage. Sensory analysis confirmed that CP-treated samples, particularly those treated with Ar, improved texture, taste, color, and aroma. **Research limitations:** This study was limited to laboratory-scale conditions and storage durations. **Originality/Value:** This research provides new insights into non-thermal postharvest preservation of pistachios and highlights cold plasma, particularly Ar-treatment, as a practical, chemical-free method to enhance quality and extend shelf life.

Keywords:
Chlorophyll content, Electrolyte leakage, Flavonoid, Phenolic content, Water activity

INTRODUCTION

Pistachio (*Pistacia vera* L.) is a commercially significant nut known for its rich nutritional content, including healthy fats, proteins, antioxidants, and essential vitamins. Due to their wide consumption and export value, pistachio is a vital agricultural product, particularly in regions such as Iran (Gheysarbigi et al., 2020). However, fresh pistachio, despite their superior nutritional profile compared to dried one, face significant postharvest quality deterioration, including mold growth, aflatoxin contamination, and textural degradation, particularly when stored under undesirable conditions. Indeed, extending the shelf life of fresh pistachio while maintaining their sensory and nutritional qualities presents a significant challenge for postharvest handling and storage.

Recent studies have highlighted the increasing interest in non-thermal preservation methods as alternatives to traditional heat treatments, which can lead to undesirable sensory changes and loss of bioactive compounds (Ramazzina et al., 2016; Tolouie et al., 2021). Cold plasma (CP), a non-thermal ionized gas consisting of reactive species such as ions, electrons, and UV radiation, has emerged as a promising technology for food preservation. Its applications in extending the shelf life of fresh produce have been studied extensively (Mao et al., 2021; Misra et al., 2014). The efficacy of CP is largely attributed to its ability to reduce microbial contamination, enhance antioxidant activity, and maintain the quality attributes of treated produce without the need for chemicals or excessive heat (Dong & Yang, 2019; Zhang et al., 2022).

Microbial contamination is a major factor influencing the quality and shelf life of fresh pistachio (Sheikhi et al., 2019a). CP has been shown to effectively reduce the growth of foodborne pathogens and spoilage microorganisms, including fungi such as *Aspergillus spp*. and *Penicillium spp*. (Park et al., 2003). The antimicrobial effects of cold plasma are primarily attributed to the reactive species produced during plasma generation, which are capable of penetrating microbial cells and disrupting their biological structures, thereby preventing microbial spoilage and extending the shelf life of the produce (Dong & Yang, 2019). In addition to its antimicrobial properties, CP treatment has been found to influence the biochemical composition of fruit, particularly phenolic compounds and flavonoids. Phenolic compounds, known for their antioxidant properties, play a crucial role in reducing oxidative stress and preserving the nutritional quality of fresh produce during storage (Hu et al., 2022). Studies have demonstrated that CP treatment can stimulate the synthesis of phenolic compounds, enhancing the antioxidant capacity of fruits such as pitaya and citrus (Li et al., 2019; Won et al., 2017). Furthermore, flavonoids, which possess both antioxidant and anti-inflammatory properties, are also significantly increased in fruits treated with cold plasma, contributing to both the preservation of quality and the enhancement of health benefits (Makari et al., 2021; Zhou et al., 2022).

Another important factor influencing the postharvest quality of pistachio is chlorophyll content. Chlorophyll is not only essential for the photosynthetic activity of plants but also serves as an indicator of the visual quality of fruits. CP has been shown to preserve chlorophyll content in various fruit, which helps maintain their green color and overall visual appeal during storage (Jia et al., 2022). This preservation of chlorophyll could potentially slow down the degradation of vital components within the pistachio, contributing to the overall retention of quality throughout storage.

In addition to improving microbial safety, enhancing antioxidant activity, and preserving chlorophyll content, CP treatment also plays a role in maintaining cell membrane integrity, which is crucial for preventing texture degradation in fruits. Studies have shown that plasma treatment reduces electrolyte leakage, indicating that CP helps to maintain the structural integrity of cell membranes, thus improving the texture and shelf life of treated fruit (Akhavan-Mahdavi et al., 2023). The ability of cold plasma to influence multiple quality parameters, including microbial load, biochemical composition, and cell membrane integrity, positions it as a highly effective non-thermal preservation method for fresh pistachio.

This study aimed to determine the optimal CP parameters for preserving the post-harvest quality of fresh pistachio. Specifically, we investigated the effects of CP treatment on shelf life extension and improvements in physical attributes related to visual appeal, water activity, and key chemical characteristics. Our findings can potentially contribute to the development of effective large-scale preservation methods for fresh pistachio, enhancing the efficiency and reliability of industrial processes. By optimizing CP treatment for fresh pistachio, we hope to provide a safe and effective method for extending their shelf life and preserving their nutritional and sensory qualities. This could have significant economic benefits for pistachio growers and processors, as well as providing consumers with access to high-quality fresh pistachio for a longer period.

MATERIALS AND METHODS

Fruit Preparation

Fresh in-hull pistachio cv. Ahmad Aghaei was harvested at horticultural maturity from 15-year-old trees in a commercial orchard in Rafsanjan, Kerman Province, Iran, carefully selected for uniform shape, size, and color, and immediately transported to the Postharvest Laboratory of the Department of Horticulture. The samples (200 ± 2 g) were placed in containers and moved downstream of the activation zone of the cold plasma (CP) region treatment (Fig. 1). Then the specimens were stored at 85 ± 5% relative humidity and 4 ± 1°C. Analyses were performed at 0, 25, and 50 days.

Cold plasma treatment

A custom-engineered plasma reactor designed for industrial applications utilizes a dielectric barrier discharge (DBD) configuration comprising a plastic reactor and plasma generator. The power electrodes consisted of six copper rods (2.8 mm in diameter) within glass tubes (3 mm internal and 5 mm external diameters) connected to a power supply delivering a sinusoidal voltage of 5–10 kV at 18 kHz, which is critical for plasma generation. The plasma voltage was measured using an oscilloscope (GWINSTEK, GDS-3502) and a high-voltage probe (Tektronix, P6015A), while the capacitor voltage was measured using a low-voltage probe. This study evaluated the plasma power consumption for various gases, estimating 6 W for oxygen (O2), 7 W for nitrogen (N2), and 11 W for argon (Ar). A fan on the plasma generator facilitated the transfer of the plasma into the reactor. Samples were treated at 5 and 8 kV using Ar, N_2, and O_2 gases. The control samples, which were placed under the same conditions without plasma activation, ensured that all other parameters remained constant.

Decay Index (DI)

At each stage of the storage, the total quantity of deteriorated fruits in the container was counted, and the percentage of decay was calculated by dividing the number of deteriorated fruit by the total number of fruit (Sheikhi et al., 2019a).

Fig. 1. Pistachio preparation and cold plasma treatment. A) Fresh pistachios of the 'Aghaei' cultivar were prepared and weighed, B) Individual pistachio samples packaged for treatment and transportation, C) Cold plasma treatment chamber containing packaged pistachio samples.

Water activity

The hull was carefully excised from each fruit specimen, and its mass was quantified using a precision digital scale. The samples were subsequently oven-dried, after which their masses were measured again. The percentage of moisture content was then calculated using the following formula:

Moisture

Moisture of samples was calculated using the following formula (1):

$$\text{Moisture (\%)} = [(\text{Initial sample mass} - \text{Final sample mass}) / \text{Initial sample mass}] \times 100 \qquad (1)$$

Sensory evaluation

A group of 10 panelists evaluated the fruit quality with an average age of 30 years. Sensory attributes, including texture, taste, color, and aroma, were assessed for each sample. The descriptive rating employed a five-point scale, where 1 represented “very bad”, 2, “poor”, 3, “average”, 4, “good”, and 5, “average” (Ehtesham Nia et al., 2022).

Total phenolic compounds (TPC)

The total phenolic content (TPC) of the fresh pistachio kernel was quantified by initially extracting the fruit pulp with phosphate buffer. To measure the TPC, 100 µl of the extract was diluted with 400 µl of phosphate buffer, 2.5 ml of 1:10 folin, and 2 ml of 5.7% sodium carbonate, followed by vortexing for 5 min in a 50°C water bath. Absorbance was measured at 760 nm using a spectrophotometer. TPC was calculated using a 1 mM gallic acid standard and expressed as mg of gallic acid equivalent per 100 g of fresh weight (Ayala-Zavala et al., 2004).

Total flavonoid and total chlorophyll

Total flavonoid content was determined by ammonium chloride colorimetry (Bor et al., 2006). The procedure involved combining 50 µl of the methanolic extract of fruit pulp with 10 µl of aluminum chloride (10%), 10 µl of potassium acetate (1 M), and 280 µl of deionized water. The samples were thoroughly agitated and incubated at room temperature for 40 min. The absorbance of the reaction mixture was measured at a wavelength of 415 nm. The total flavonoid content was quantified using a quercetin standard curve.

To quantify the total chlorophyll content, 0.25 g of fresh fruit peel sample was homogenized in a porcelain mortar with 10 ml of 80% acetone until a uniform solution was obtained. Subsequently, the resulting solution was transferred to a Falcon tube and centrifuged at 3500 rpm for 10 min. The optical absorption of the solution was measured using a spectrophotometer at wavelengths of 645, 652, and 663 nm. Finally, the chlorophyll concentration was calculated using the following equation (2) (Arnon, 1949):

$$\text{Chlorophyll a (mg/g fwt)}=[12.7\times(\text{OD}.663)-2.69]\times[(\text{OD}.645)\times V/1000\times W]$$

$$\text{Chlorophyll b (mg/g fwt)}=[22.9\times(\text{OD}.645)-4.68]\times[(\text{OD}.663)\times V/1000\times W]$$

$$\text{Total Chlorophyll (mg/g fwt)}=[\text{OD}652\times1000/34.5]\times[V/1000\times W] \qquad (2)$$

W = sample weight
V = the volume of acetone consumed

Microbial activity

Microbial activity was evaluated using a modified version of the method described by Sheikhi et al. (2019a). Briefly, 10 g of pistachio hull was finely ground and homogenized in 90 mL of peptone water for 10 min using a stomacher. The homogenate was then subjected to a tenfold serial dilution, ranging from 10 ^{1} to 10^{-4}. From each dilution, 1 mL was aseptically transferred, in duplicate, into pre-warmed (44–47 °C) Petri dishes containing Plate Count Agar (PCA), thoroughly mixed, and allowed to solidify. The plates were incubated aerobically at 28 ± 1 °C for 3–4 days, after which colony-forming units (CFU) were enumerated. The microbial population was expressed as log CFU per gram of fresh weight (log CFU g^{-1}).

Statistical analysis

Statistical analysis was conducted using SAS software to evaluate the significance of differences among treatments and storage durations (0, 25, and 50 days). The experimental design employed was a completely randomized factorial design with three replicates. Analysis of variance (ANOVA) revealed significant effects, and Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$ was utilized to identify significant differences between treatment means.

RESULTS

Decay index (DI)

The DI increased with prolonged storage across all groups; however, CP treatment significantly ($p \leq 0.05$) inhibited decay compared to the control (Fig. 2). Initially, no decay was observed in any samples. Over time, microbial spoilage became evident, with Ar-CP treatments (both 5 kV and 8 kV) exhibiting the most pronounced inhibitory effects.

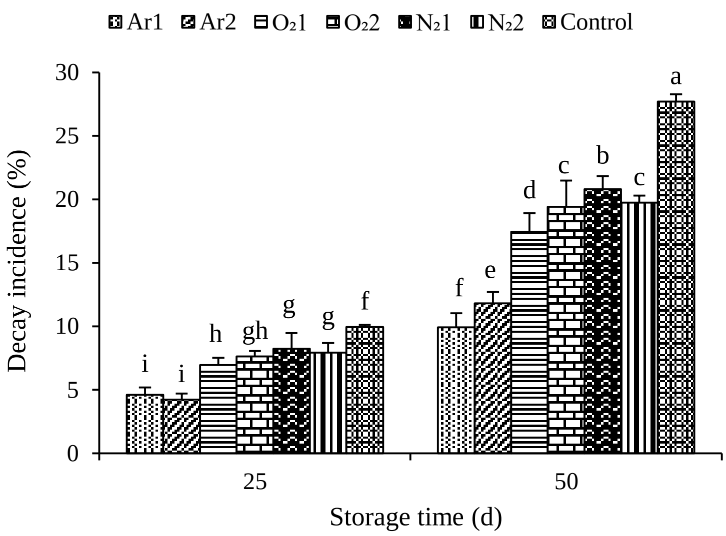

Fig. 2. Effect of CP treatment argon (Ar), nitrogen (N_2), and oxygen (O_2) at 5 kV (1) and 8 kV (2) on decay index of fresh pistachio during 50 days of storage at 4°C. Vertical bars represent the mean ± SE. Different letters (above the bars indicate significant differences ($p \leq 0.05$) between treatments at each storage time.

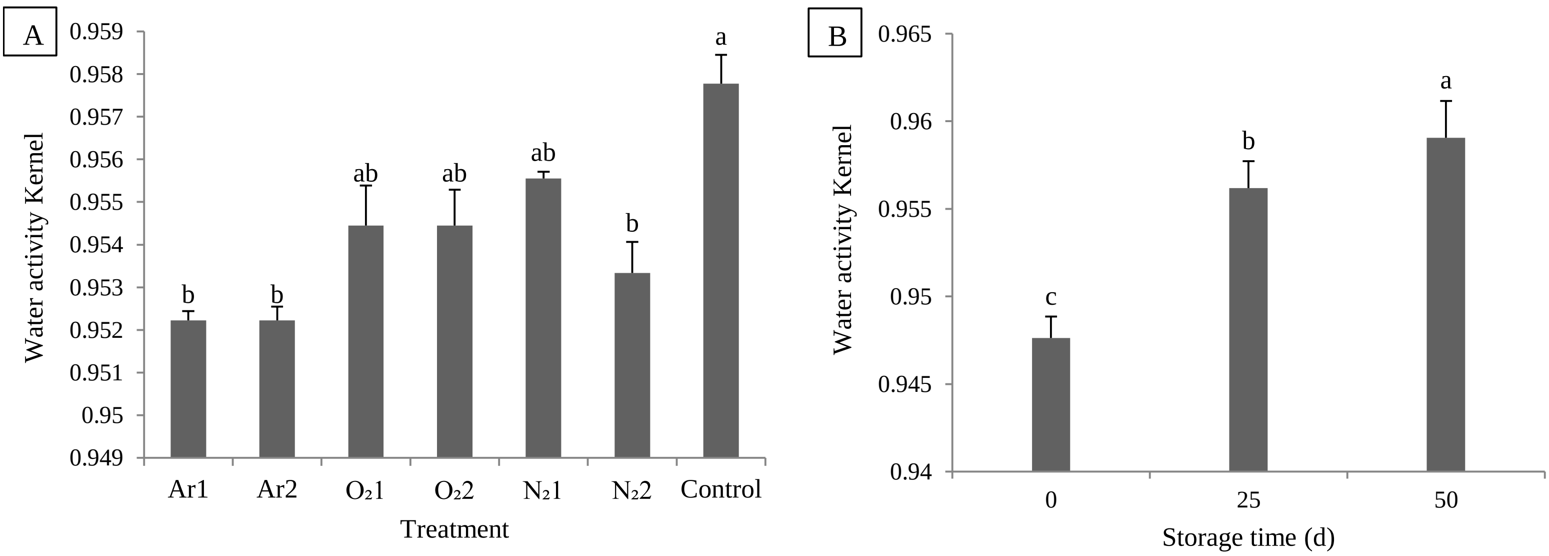

Fig. 3. Effect of CP treatment with argon (Ar), nitrogen (N_2), and oxygen (O_2) at 5 kV (1) and 8 kV (2) on the water activity of fresh pistachio kernels (A) and during 50 days of storage at 4°C (B). Vertical bars represent the mean ± SE. Different letters above the bars indicate significant differences ($p \leq 0.05$) between treatments at each storage time.

Water activity

Figure 3 indicates that the plasma treatment had a significant effect on the water activity of the fresh pistachio ($p < 0.05$), while the effects of treatments and storage time interaction were not significant ($p > 0.05$). The water activity values for the control and cold plasma (Ar1, Ar2, $O_2$1, $O_2$2, $N_2$1and $N_2$2) treated samples were 0.957, 0.952, 0.952, 0.954, 0.954, 0.955, and 0.953, respectively. Fresh pistachio treated with Ar1 and Ar2 exhibited the lowest water activity with relatively similar values. In contrast, the control sample exhibited the highest water activity (Fig. 3A). The water activity of fresh pistachio exhibited an overall increase as the storage period increased (Fig. 3B).

Total phenolic content

The effect of plasma treatment on the total phenolic content of fresh pistachio is illustrated in Figure 4. The highest total phenolic content was observed in the N_2 plasma treatment, whereas the lowest amounts were observed in the Ar_2 and $O_2$1 treatments as well as in the control. During the initial storage interval (25 d), the highest phenolic content (0.403 mg GAE/100 g) was observed in the Ar1 plasma-treated samples. During the subsequent interval (50 d), the highest content (0.485 mg GAE/100 g) was observed in the $N_2$2 plasma-treated samples.

Sensory evaluation

Figure 5 shows a comparison of the average sensory evaluation scores of pistachio samples. The sensory attributes at the end of the storage period were markedly affected by the plasma treatment. Notably, fresh pistachio subjected to Ar1, Ar2, and $O_2$1 plasma treatments displayed significantly elevated mean sensory scores in terms of texture, taste, color, flavor, and appearance on storage day 25. Moreover, after 50 days of storage, all plasma-treated samples exhibited significantly higher scores than the control.

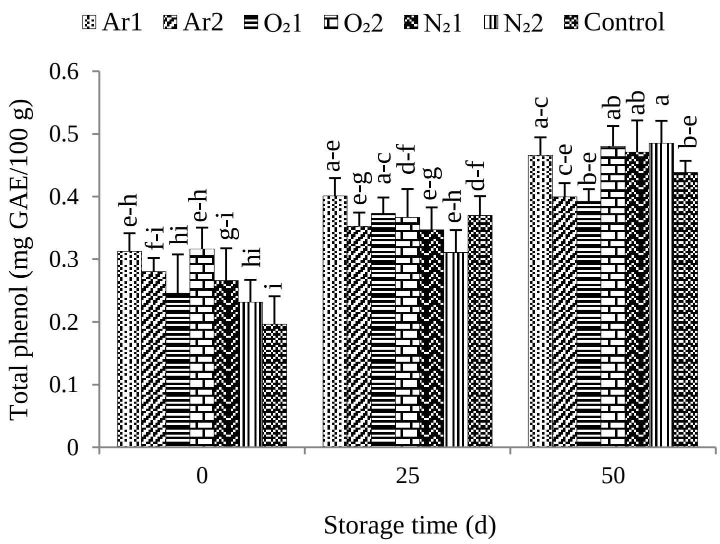

Fig. 4. Effect of CP treatment argon (Ar), nitrogen (N_2), and oxygen (O_2) at 5 kV (1) and 8 kV (2) on total phenolic content of fresh pistachio during 50 days of storage at 4°C. Vertical bars represent the mean ± SE. Different letters (above the bars indicate significant differences ($p \leq 0.05$) between treatments at each storage time.

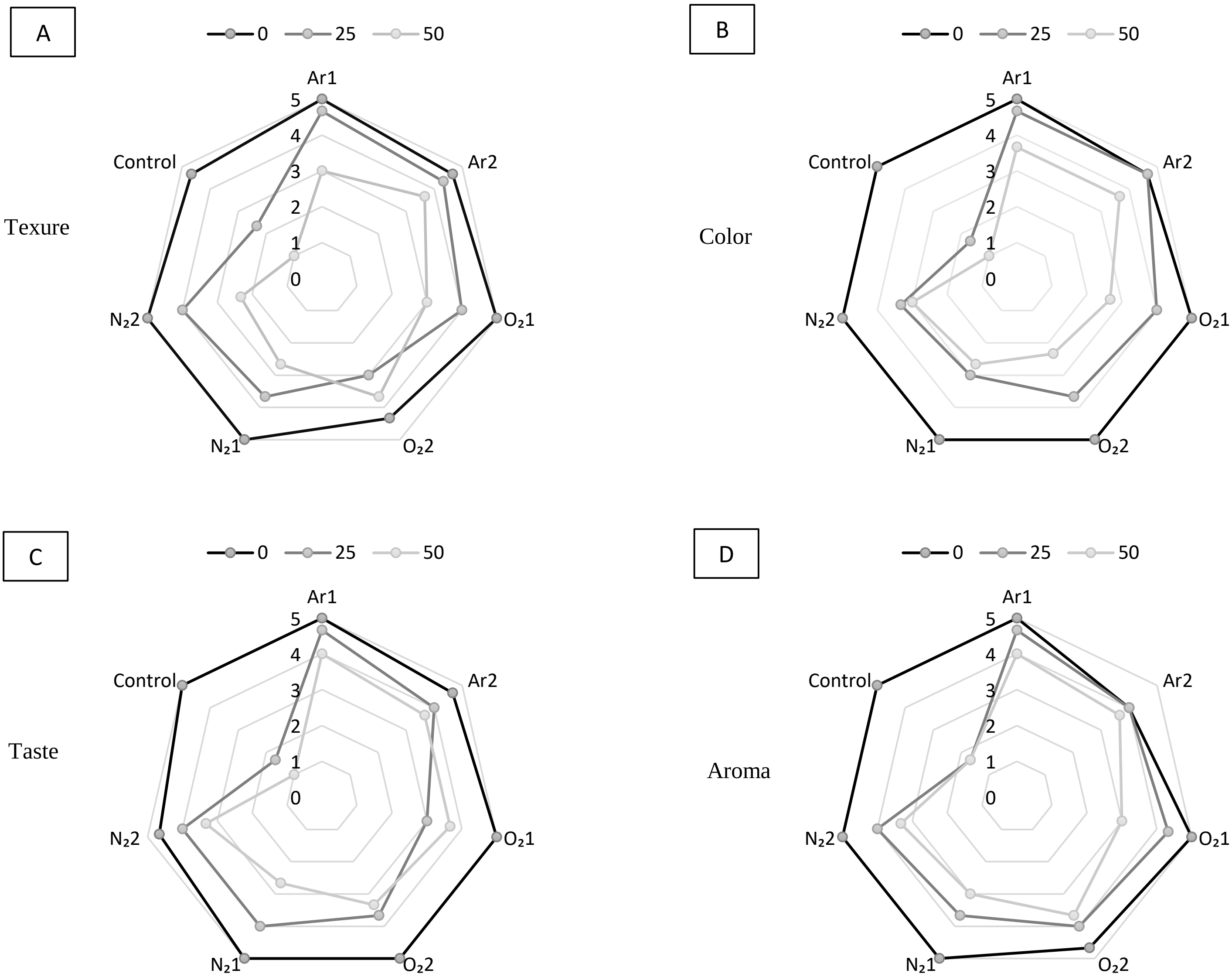

Fig. 5. Effect of CP treatment argon (Ar), nitrogen (N_2), and oxygen (O_2) at 5 kV (1) and 8 kV (2) on the sensory attributes of fresh pistachios, including texture (A), color (B), taste (C), and aroma (D), during 50 days of storage at 4 °C.

Total chlorophyll content and Total flavonoid content (TFC)

The present study demonstrated that plasma treatment exerted a statistically significant effect ($P < 0.05$) on the total chlorophyll content of fresh pistachio. Figure 6A depicts pistachio subjected to plasma treatment exhibited significantly elevated total chlorophyll levels over a 50-day storage period. At the 25-day storage interval, the highest and lowest total chlorophyll contents were observed in pistachio treated with $N_2$2 and $N_2$1 and the control, respectively, measuring 2.96, 2.89, and 2.17 g. kg^{-1} FW, respectively.

Figure 6B illustrates the effect of cold plasma treatment on the TFC during the storage period. The results indicated that fresh pistachio subjected to A1, Ar2, and $N_2$2 treatments on the 25th day exhibited higher flavonoid contents (17.04, 18.11, and 16.91 g. kg^{-1}, respectively) than the other treatments. At the end of the storage period, TFC was highest in the Ar1 plasma treatment (16.02 g kg^{-1}) and lowest in the control (13.0 g kg^{-1}).

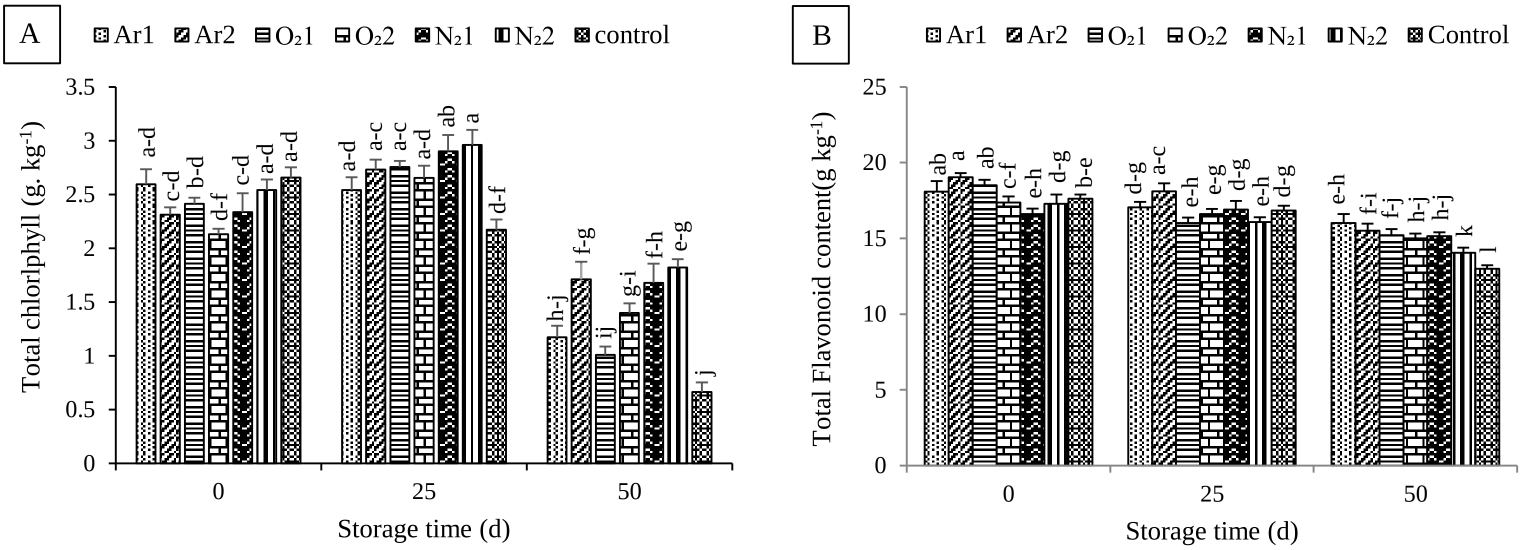

Fig. 6. Effect of CP treatment argon (Ar), nitrogen (N_2), and oxygen (O_2) at 5 kV (1) and 8 kV (2) on total chlorophyll content (A) and total flavonoid content (B) of fresh pistachios during 50 days of storage at 4°C. Vertical bars represent the mean ± SE. Different letters (above the bars indicate significant differences ($p \leq 0.05$) between treatments at each storage time.

Electrolyte leakage (EL)

Electrolyte leakage of fresh pistachio stored at 4℃ increased during 50 days of storage (Fig. 7). At 25 d of storage, the EL in Ar plasma-treated samples was lower than that of the other treatments and the control. On day 50, the highest and lowest EL values were observed in the Ar plasma-treated and control groups (74.82 % and 88.67 %, respectively).

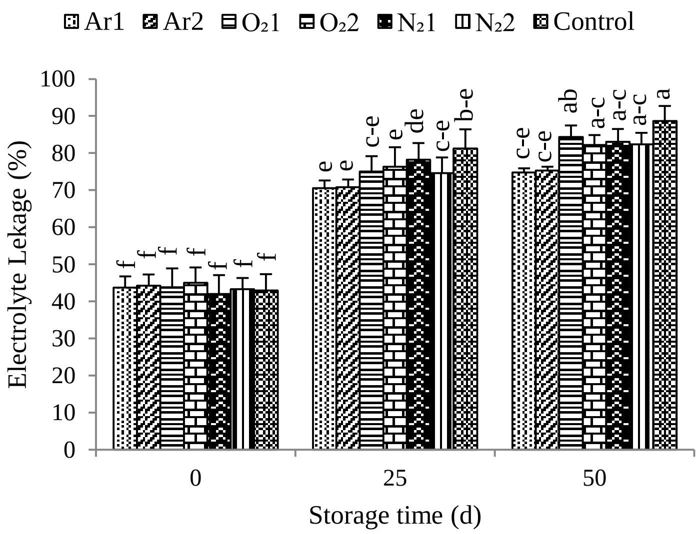

Fig. 7. Effect of CP treatment argon (Ar), nitrogen (N_2), and oxygen (O_2) at 5 kV (1) and 8 kV (2) on Electrolyte leakage of fresh pistachios during 50 days of storage at 4°C. Vertical bars represent the mean ± SE. Different letters (above the bars indicate significant differences ($p \leq 0.05$) between treatments at each storage time.

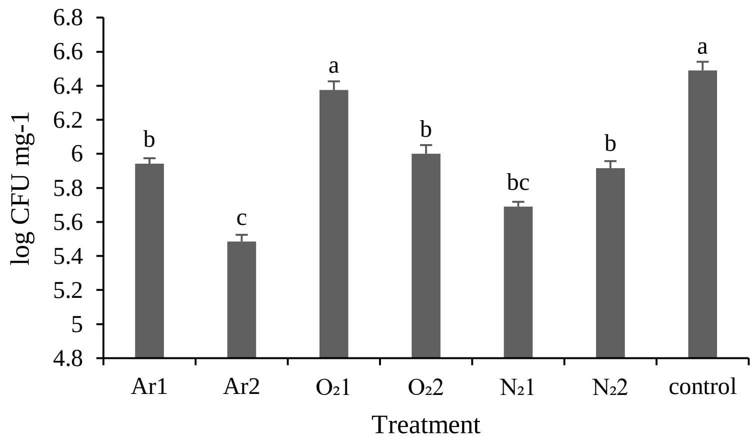

Fig. 8. Effect of CP treatment argon (Ar), nitrogen (N_2), and oxygen (O_2) at 5 kV (1) and 8 kV (2) on microbial activity of fresh pistachio during 50 days of storage at 4°C. Vertical bars represent the mean ± SE. Different letters (above the bars indicate significant differences ($p \leq 0.05$) between treatments at each storage time.

Microbial activity

The impact of cold plasma (CP) treatments with different gases and voltages on the microbial counts of fresh pistachios after 50 d of storage at 4 °C is illustrated in Figure 8. Significant variations were observed among the treatments ($p < 0.05$). The highest microbial loads were detected in the control (6.5 log CFU mg^{-1}) and $O_2$1 (6.45 log CFU mg^{-1}), which were statistically similar and represented the least effective conditions for microbial reduction. Ar1 (6.0 log CFU mg^{-1}), $O_2$2 (6.0 log CFU mg^{-1}), and $N_2$2 (6.0 log CFU mg^{-1}) exhibited moderate reductions compared to the control, whereas $N_2$1 showed a further decrease, reaching 5.7 log CFU mg^{-1}. The lowest microbial count was recorded in Ar2 (5.5 log CFU mg^{-1}), which was significantly lower than that in all other treatments, highlighting its superior antimicrobial efficacy.

DISCUSSION

Dielectric barrier discharge plasma represents an innovative processing technique that demonstrates considerable potential for preserving quality and inhibiting microbial proliferation in fruit and vegetable. This study aimed to investigate the efficacy of cold plasma treatment as a novel preservation technique for fresh pistachio. The effects of argon, nitrogen, and oxygen gases at 5 and 8 kV on the physiological quality of pistachio was evaluated during cold storage.

The observed variations in total phenolics and flavonoids during storage appear to be closely associated with the postharvest shelf life of fresh pistachios. Phenolic compounds and flavonoids are important secondary metabolites with strong antioxidant potential, and their retention can contribute to delaying oxidative damage and microbial spoilage. Tsantili et al. (2011) reported that both total phenolics and flavonoids in pistachio kernels were influenced by cultivar type and storage conditions, and higher levels were positively correlated with enhanced antioxidant capacity, thereby supporting longer preservation of nut quality. Studies have indicated that cold plasma (CP) can activate essential enzymes responsible for phenolic compound production, thereby enhancing phenol synthesis. This evidence suggests that CP application may be a viable strategy to boost the formation of phenols and flavonoids in fruit during the post-harvest period (Misra et al., 2014). Plasma technology, as a non-thermal food preservation method, has gained considerable attention due to its potential to improve the shelf life of perishable produce without the use of chemicals or high temperatures (Zhang et al., 2022). The results from this study suggest that cold plasma treatment could be a promising solution to address the challenges of postharvest deterioration in pistachio, a crucial crop with high commercial value.

Decay is one of the most significant physical alterations that occur during storage and can directly influence food quality (Khan et al., 2023). The decay index (DI) results further emphasize the positive impact of plasma treatment on the prevention of postharvest decay. The plasma treatments, particularly those using argon, significantly reduced the incidence of decay in pistachios compared to the control group. In the present study, the application of postharvest cold plasma treatments exhibited a pronounced inhibitory effect on decay development compared to the control group throughout the storage period. The rapid and intensive postharvest decay of fresh pistachios is primarily attributed to microbiological deterioration with *Aspergillus* spp (Sheikhi et al., 2019b). At both 5 kV and 8 kV, the plasma treatments inhibited microbial activity and delayed spoilage, which could be attributed to the antimicrobial effects of cold plasma. Park et al. (2003) suggest that the reactive species and ultraviolet radiation produced in plasma can penetrate fungi with ease and interact directly with the biological materials within the fungal cells. Similar effects were observed in blueberries subjected to DBD plasma treatment; the decay rates decreased by 17.7%, 14.3%, and 5.2% after 20 days of storage for treatment durations of 6, 8, and 10 min, respectively (Dong & Yang, 2019).

Several studies have demonstrated the efficiency of cold plasma (CAP) in microbial reduction and quality preservation of fresh produce. For example, the application of low-pressure CAP on dried walnut kernels achieved a 3.1 log CFU/g reduction in total mesophilic bacteria and a 2.8 log CFU/g reduction in yeast and mold counts, while retaining the kernels' color, lipid stability, and peroxide value within acceptable limits (Ahangari et al., 2021). Similarly, when applied to fresh strawberries under modified atmosphere conditions, CAP reduced the native microbial population on the fruit surface by approximately 2.5 log CFU/g, thereby extending the shelf life up to 7 days without compromising firmness or antioxidant activity (Misra et al., 2014). Moreover, CAP treatment of grapes inoculated with Botrytis cinerea resulted in a 3.6 log CFU/g reduction in fungal load, while preserving physicochemical properties such as soluble solids content, titratable acidity, and color during storage (Khalaj et al., 2024).

Collectively, these results indicate that the antimicrobial efficacy of CAP primarily derives from the generation of reactive oxygen and nitrogen species, UV photons, and ozone, which disrupt microbial membranes and metabolic processes(Lacombe et al., 2015).

One of the key indicators of quality in fresh pistachio is the integrity of cell membranes, as it directly influences the fruit's texture, water retention, and resistance to pathogens (Tajeddin & Shakerardekani, 2022). Our results demonstrated a significant reduction in electrolyte leakage (EL) in plasma-treated pistachio, particularly those treated with argon (Ar) plasma at both voltage levels (5 kV and 8 kV). The lowest EL values were observed on day 50 of storage in the Ar plasma-treated groups (74.82%), which indicates better preservation of membrane integrity compared to the control group (88.67%). This finding is consistent with previous studies that show plasma treatment helps to preserve cell membrane function by reducing oxidative stress and enhancing membrane stability (Abarghuei et al., 2021). Nasibi et al. (2024) demonstrated that plasma-activated water (PAW) significantly affected rose flowers, with the 5-minute treatment being the most effective, reducing ion leakage by 42-47% compared to the control.

The reduction in EL suggests that plasma treatment could be effective in maintaining cellular function and quality during storage, thus potentially extending the shelf life of pistachio (Akhavan-Mahdavi et al., 2023). Water activity plays a crucial role in determining the microbial stability and overall quality of pistachios during storage. In this study, plasma-treated pistachios exhibited lower water activity compared to the control, especially those treated with argon at both voltage levels. This reduction in water activity could contribute to the preservation of fruit texture and the inhibition of microbial growth, as lower water activity typically limits the growth of spoilage microorganisms (Akhavan-Mahdavi et al., 2023). Moreover, the decreased water activity observed in plasma-treated pistachio suggests that plasma treatment may help in reducing moisture loss, which is critical in maintaining the fresh and appealing characteristics of pistachio during storage (Rao et al., 2023).

Cold plasma treatment also significantly influenced the biochemical composition of pistachio, particularly in terms) and total flavonoid content (TFC). The TPC was found to be highest in the $N_2$2 plasma treatment, whereas the Ar1 and Ar2 treatments also exhibited relatively high TPC. These findings are significant because phenolic compounds are known for their antioxidant properties, which help protect fruits from oxidative damage during storage (Ramazzina et al., 2016). The increased phenolic content in plasma-treated pistachios is consistent with studies showing that plasma treatment can enhance the production of antioxidant compounds, thus improving the postharvest quality of fruits (Li et al., 2019). Similarly, plasma treatment led to increased flavonoid content, with the highest levels observed in pistachios treated with Ar1, Ar2, and $N_2$2. This increase in flavonoids further supports the idea that plasma treatment can stimulate the synthesis of bioactive compounds, contributing to both the preservation and enhancement of pistachio quality (Makari et al., 2021).

An interesting aspect of the study was the impact of plasma treatment on the total chlorophyll content of pistachio. Plasma treatment led to increased chlorophyll levels, which is an important factor for maintaining the visual appeal and freshness of the pistachios. The preservation of chlorophyll could also indicate that plasma treatment helps maintain the overall metabolic activity of the fruit during storage, contributing to the preservation of its green color and other essential quality traits (Bussmann et al., 2023). The results suggest that plasma treatment may help in maintaining the photosynthetic capacity or chloroplast integrity of pistachios, thus slowing down the degradation of these vital components during storage (Jia et al., 2022).

Sensory evaluation demonstrated that plasma treatment significantly enhanced the sensory attributes of pistachio, including texture, taste, color, flavor, and overall appearance. Notably, the Ar1 and Ar2 plasma-treated groups consistently achieved higher sensory scores compared to the control group, indicating a substantial improvement in overall acceptability. These findings suggest that plasma treatment not only preserves the biochemical and physiological quality of pistachios but also enhances their organoleptic properties, making them more appealing to consumers. The positive sensory attributes observed in plasma-treated pistachio was consistent with previous research demonstrating the beneficial effects of plasma on maintaining the texture, flavor, and color of various fruit (Shirani et al., 2020; Zhou et al., 2022) This enhancement of sensory properties could potentially increase the market value of plasma-treated pistachio, making them a more attractive option for both producers and consumers.

CONCLUSION

In summary, the results of this study provide compelling evidence that CP treatment, particularly with argon gas at 5 and 8 kV, represents a promising non-thermal approach for the postharvest preservation of fresh pistachio. Plasma treatment significantly reduced electrolyte leakage, inhibited microbial spoilage, maintained optimal water activity, enhanced antioxidant capacity, and improved sensory characteristics, all of which collectively contributed to a notable extension of shelf life. Overall, these results strongly suggest that cold plasma treatment is a highly effective and environmentally friendly alternative to conventional postharvest preservation methods. This approach not only prolongs the shelf life of pistachios but also helps maintain their overall quality, ensuring that they retain desirable characteristics throughout storage and transportation.

Conflict of interest

The authors declare that they have no conflict of interest.

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