

Improving Disinfection and Packaging Strategies for the Effective Preservation of Welsh Onion (*Allium fistulosum* L.)

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Abstract

This study aimed to improve postharvest preservation strategies for Welsh onion (*Allium fistulosum* L.) by optimizing disinfection techniques and packaging methods. Conducted in two phases, the first involved disinfection using gamma irradiation (1, 3, and 5 kGy) and cold plasma (15, 20, and 25 kV for 5, 10, and 15 minutes). In the second phase, four gas-barrier nanocomposite films were tested under ambient and vacuum-sealed storage for 4, 8, and 12 months. Volatile compounds were analyzed via gas chromatography (GC and GC/MS). Cold plasma was more effective than gamma irradiation in preserving key postharvest quality parameters. The highest phenolic content and antioxidant activity were found in samples treated with cold plasma at 20 and 25 kV for 5 minutes. Nonetheless, all packaging treatments experienced declines in total phenolics, essential oil yield, and L* color values over time. Major volatile compounds in the essential oil included dipropyl disulfide, dipropyl trisulfide, dimethyl trisulfide, diallyl disulfide, and d-limonene. This study introduces an innovative approach that combines cold plasma treatment with nanocomposite-based packaging to extend shelf life and preserve the functional and sensory qualities of fresh vegetables during long-term storage. These findings offer valuable insights for postharvest management of leafy vegetables like Welsh onion.

Introduction

Allium vegetables, such as onions, garlic, and leeks, are essential to human health due to their nutritional value and medicinal properties¹. Welsh onion (*Allium fistulosum* L.), also known as stone leek, Chinese onion, Chinese spring onion, and Japanese bunching onion, is a highly popular medicinal and functional vegetable in East Asian countries^{2,3}. It has been reported to exhibit various biological activities, including antioxidant, anti-inflammatory, antifungal, and antimicrobial effects⁴. Furthermore, the green pseudostems, leaves, and undeveloped bulbs of Welsh onion are commonly used as a seasoning in a variety of culinary applications, including cooked dishes, salads, and pickles⁵. Moreover, volatile compounds and extracts derived from Welsh onion have shown notable antimicrobial, antifungal, antioxidant, and antiparasitic properties^{6,7}. The biological activity of *Allium fistulosum* is strongly associated with its total phenolic content⁸. Additionally, flavonoids such as quercetin and its glycosides have been linked to the antioxidant and anticancer properties of Welsh onion⁹.

Proper storage conditions are essential after harvesting vegetables and spices, with temperature and humidity being critical factors^{10,11}. Maintaining low temperatures helps preserve quality and extend shelf life by slowing down deterioration processes¹². Additionally, controlling relative humidity is vital because excessive humidity may lead to condensation, promoting microbial contamination and posing significant health risks¹³.

Consequently, implementing effective disinfection strategies is crucial to mitigate microbial contamination and ensure the safety of vegetables and spices after harvest¹⁴. With rising demand for safe, fresh-like produce, various disinfection technologies have been developed¹⁵. However, some methods may not fully meet food safety and quality standards, necessitating the identification of more effective solutions¹⁶.

Common disinfection methods for medicinal plants include irradiation steam treatment, high hydrostatic pressure, high temperatures, ionizing radiation, infrared radiation, and the use of ethyl alcohol or formaldehyde¹⁷. Short shelf-life products are disinfected using physical methods (like irradiation and heat) and newer chemical alternatives (like ozone and essential oils) to meet modern safety standards¹⁸.

Irradiation is a highly effective physical method for disinfecting and preserving food and plants, and it has been shown to better maintain quality and properties compared to traditional chemical methods¹⁹. Recommended doses of gamma radiation for inhibiting sprouts doses used are < 0.5 kGy for hindering ripening; lower or equal than 1 kGy for pest disinfestations; and 3–5 kGy to increase shelf-life and for pathogenic microbes²⁰. Studies have shown that gamma radiation at doses of 1 kGy and 5 kGy significantly reduces microbial contamination and extends the shelf life of various vegetables, particularly those that are dry, bulbous, or root-based²¹. In Iran, gamma irradiation at doses of 90 to 150 Gy applied to Iranian onion cultivars (White-Ghom, White-Neyshabour, Red-Ridge-Lump, and Red-Ray-Corrugated) significantly improved their post-harvest shelf life and quality²². Colletti, et al.²³ found that gamma irradiation treatments (up to 1.0 kGy), combined with modified atmosphere packaging, produced high-quality peach products with an extended shelf life. Adiani, et al.²⁴ reported that gamma irradiation at 10 kGy

enhanced the extractability of oil and phenolic compounds by 80% and 50%, respectively. Low-energy e-beam irradiation at 18 kGy effectively reduced microbial contamination in black peppercorns without affecting their chemical or microbial integrity²⁵.

Atmospheric cold plasma (ACP) is an emerging, non-destructive preservation technology with promising potential for extending the shelf life of fruits and vegetables²⁶. Researchers reported that cold atmospheric plasma treatments reduced the total microbial count, as well as mold and yeast levels in cherry tomatoes²⁷, fresh-cut pears²⁸, spring onion²⁹ and other consumed vegetables³⁰. Kazemzadeh, et al.³¹ found that plasma treatment (8 kV, 8.83 min, 6.6 cm) enhanced vitamin C retention and antioxidant activity in onion leaves during ten days of refrigerated storage. Senguler, et al.³² showed that cold plasma treatment of onion skin waste reduced microbial counts while enhancing total phenolic content (TPC) and antioxidant activity. The cold plasma technique is particularly suitable for temperature-sensitive products and offers an eco-friendly³³, cost-effective, and non-chemical alternative for preservation³⁴.

Due to their typical patterns of consumption, vegetables and spices are often stored for extended periods³⁵. Therefore, selecting appropriate packaging materials is essential. Several studies have investigated how different packaging types influence the qualitative and quantitative attributes of these products³⁶. Packaging plays a key role in maintaining the quality of vegetables and herbs during storage³⁷. For example, vacuum packaging slightly increased flavonol content in onions, though anthocyanins declined³⁸. Polyethylene covers and cold, dark storage preserved active compounds in dried purple coneflower³⁹. In contrast, storing basil (*Ocimum basilicum*) in paper or plastic for up to 12 months had little effect on essential oil content⁴⁰. Similarly, polyethylene packaging reduced moisture loss in garlic, and modified atmosphere packaging helped retain chlorophyll in coriander⁴¹. The selection of appropriate disinfection methods and storage conditions for vegetables and spices depends on their intended application, the specific plant parts used, and the nature of their bioactive compounds⁴². Accordingly, the present study aimed to optimize a disinfection approach and determine suitable packaging solutions for Welsh onion (*Allium fistulosum*), a plant valued both for its medicinal properties and as a culinary ingredient, particularly in pancakes.

Results

Disinfection

Total phenolic content

The results of the study indicated that the method of disinfection had a significant impact on the phenolic compounds present in *A. fistulosum* L. samples. Gamma irradiation, in particular, caused a notable decline in total phenolic content, with the lowest concentration measured at a dose of 5 kGy, reaching 19.5 mg GAE/g DW (Figure 1). Conversely, samples exposed to cold plasma exhibited higher levels of total phenols compared to those treated with gamma rays. The peak phenolic content was observed in samples treated with cold plasma at 25 kV for 5 minutes, registering 196.84 mg GAE/g DW (Figure 1).

Antioxidant Activity (DPPH)

Comparative evaluation of the antioxidant activity of *A. fistulosum* L. extracts using the DPPH assay revealed that cold plasma treatment at 25 kV for 5 minutes resulted in the highest radical scavenging capacity, with an IC₅₀ value of 78.74 µg/mL (Figure 1). In contrast, the lowest antioxidant activity was observed in samples exposed to 5 kGy gamma irradiation, which also showed an IC₅₀ value of 78.74 µg/mL, indicating minimal improvement over the control. Notably, increasing the cold plasma intensity from 15 kV to 25 kV over a fixed 5-minute treatment period led to a marked enhancement in antioxidant potential, as reflected by a significant reduction in IC₅₀ values from 168.36 µg/mL to 78.74 µg/mL.

Color characteristics

The analysis of color indices in treated plants revealed that the b* index was significantly affected by the disinfection methods, whereas the L* and a* indices were not significantly affected (Table 3). Gamma radiation treatment, particularly at higher intensities, caused a reduction in the b index. The control samples exhibited the highest b values, followed by cold plasma treatment at 25 kV for 10 minutes, with recorded values of 22.39 and 21.89. At 15 kV cold plasma intensity, a longer treatment

duration (5 to 15 minutes) increased the b^* index. However, at the highest cold plasma intensity (25 kV), extending the disinfection duration to 15 minutes caused a decrease in the b^* index value (Table 3). Cold plasma treatment at 20 kV for 10 minutes resulted in the highest L index, whereas the lowest value was recorded at 25 kV for the same duration. Both the 3 kGy gamma radiation and the cold plasma treatment at 25 kV for 15 minutes resulted in the highest a^* index values.

Essential oil content and composition

Different disinfection techniques had a notable impact on the essential oil content of *A. fistulosum* L. Among the tested methods, cold plasma treatment at 15 kV and 20 kV for 15 minutes yielded the highest essential oil concentration, reaching 0.54% w/w (Figure 2). This level was more than three times greater than that obtained from a 1-minute exposure at the same voltages. Furthermore, gamma irradiation at doses of 3 and 5 kGy also enhanced the essential oil content compared to the lower dose of 1 kGy.

Gas chromatographic analysis of the essential oil components indicated that dipropyl disulfide was the predominant compound across all disinfection treatments, with its highest concentration (18.3%) detected in samples exposed to 5 kGy of gamma irradiation (Table 4). Dipropyl trisulfide was identified as the second most abundant constituent, reaching its maximum level in plants treated with cold plasma at 20 kV for 10 minutes. Overall, sulfur-containing compounds including dipropyl disulfide, dipropyl trisulfide, dimethyl trisulfide, diallyl disulfide, and methyl propyl trisulfide constituted the major fraction of the essential oil profile, accounting for 80.0% to 92.3% of total oil content (Table 4). The highest cumulative proportion of these sulfur compounds (92.3%) was recorded following cold plasma treatment at 15 kV for 15 minutes. An increase in gamma radiation intensity was associated with elevated levels of these compounds. A comparable pattern was observed under cold plasma treatment at 15 kV, where prolonged exposure times led to a progressive enhancement in their concentrations.

Packaging

Total phenolic content

The application of various packaging methods had a significant impact on the phenolic compound content in *A. fistulosum* L. samples. A general decline in total phenolic content was observed across all packaging treatments as storage duration increased from 4 to 12 months (Figure 3). Notably, treatments PF1A, PF3V, and PF4AV exhibited approximately a 50% reduction in phenolic content between months 4 and 8. Among the tested conditions, the highest phenolic content after 4 months of storage was recorded in treatment PF3A, with a value of 162.72 mg GAE/g DW. In contrast, the lowest phenolic content after 12 months was observed in PF4V, with 57.4 mg GAE/g DW (Figure 3).

Antioxidant Activity (DPPH)

Comparative analysis of the antioxidant activity of *A. fistulosum* L. extracts using the DPPH assay indicated that the PF3A treatment exhibited the highest radical scavenging capacity, with an IC_{50} value of 84.36 μ g/mL (Figure 3). Conversely, the lowest antioxidant activity was observed in PF4V after 8 months of storage, with an IC_{50} value of 262.0 μ g/mL. On average, the PF3A treatment exhibited the highest antioxidant activity among all coatings across the three storage periods (4, 8, and 12 months), with a mean IC_{50} value of 113.0 μ g/mL.

Color characteristics

The analysis of color indices (L^* , a^* , and b^*) in *A. fistulosum* L. revealed that storage duration had a significant impact across all packaging methods (Table 5). The L^* index, representing lightness, consistently decreased with longer storage periods. The highest L^* value (53) was observed in the PF1A sample at 4 months, while the lowest was recorded in the PF3V control at 12 months. The a^* index, which reflects the red-green spectrum, reached its peak in the PF2V treatment after 12 months, with a value of 9.7 (Table 4). For the b^* index (yellow-blue spectrum), the most notable increase occurred in the PF4V treatment after 12 months, indicating a pronounced shift toward yellow (Table 5).

Essential oil content and composition

The amount of essential oil in plant samples was affected by both packaging methods and storage periods. In the PF1V, PF2A, and PF3A packaging types, extending the storage time from 4 to 12 months led to a decline in essential oil levels. Conversely, in treatments PF2V, PF3V, PF4A, and PF4V, the essential oil concentration peaked at 6 months, surpassing levels observed at 3 and 9 months, with PF4A at 6 months showing the highest recorded value (Figure 4). Overall, the lowest essential oil contents across all treatments were observed after 12 months of storage.

The essential oil analysis indicated that the primary constituents across all packaging treatments included dipropyl trisulfide (9.4%–16.4%), dipropyl disulfide (9.0%–16.3%), methyl propyl trisulfide (8.1%–14.3%), diallyl disulphide (6.8%–10.7%), dimethyl trisulfide (5.3%–10.5%), and d-limonene (4.0%–9.1%). In packaging PF1 under vacuum conditions, there was a notable reduction in the concentrations of key sulfur-containing compounds such as dipropyl disulfide, methyl propyl trisulfide, dimethyl trisulfide, and diallyl disulphide. This decline was further intensified with extended storage duration (Table 6). Additionally in packaging PF1, d-limonene, a monoterpene, exhibited an increase in quantity under vacuum conditions compared to packaging in ambient air.

In the PF2A packaging (normal atmospheric conditions), prolonged storage led to an increase in dimethyl trisulfide levels, while dipropyl trisulfide and d-limonene concentrations decreased (Table 7). In contrast, under vacuum packaging (PF2V), extending storage from 4 to 12 months caused a decline in dimethyl trisulfide, along with similar reductions in methyl propyl trisulfide, diallyl disulfide, and dipropyl disulfide. Overall, the total sulfur-containing compounds in PF2 packaging decreased from 76.3% to 69.9% under atmospheric conditions, and from 76.0% to 61.2% under vacuum, when storage time increased from 4 to 12 months (Table 7).

In PF3 packaging, the total sulfur-containing compounds decreased with extended storage under both atmospheric and vacuum conditions (Table 8). In contrast, d-limonene content increased over time in normal air but declined under vacuum. Additionally, the concentrations of 2-dodecanol and 2-tridecanone classified as hydrocarbon compounds increased under both storage conditions between 4 and 12 months. These two compounds typically represent over 70% of the essential oil content.

In PF4 packaging, a noticeable decline in sulfur-containing compounds was observed as storage time increased, regardless of whether the samples were kept under atmospheric or vacuum conditions. Interestingly, d-limonene exhibited contrasting behavior depending on the storage environment it gradually decreased under normal atmospheric conditions but increased when stored under vacuum (Table 9). Over the 4 to 12 month storage period, the total sulfur compounds in PF4 dropped from 79.1% to 73.8% in air, and from 86.2% to 74.1% in vacuum-sealed samples, indicating a greater loss under vacuum conditions despite the temporary rise in certain volatile components like d-limonene.

Discussion

Various disinfection techniques markedly influenced the total phenolic content observed in the samples. This outcome is consistent with earlier research indicating that such methods including gamma irradiation can alter the phenolic levels in plant materials⁴³. It has been proposed that the effectiveness of irradiation on plant constituents depends on several factors, such as the radiation dose, exposure time, and the characteristics of the raw material^{44,45}.

In the present study, gamma irradiation at a dose of 3 kGy led to an increase in the phenolic content of *A. fistulosum* L., although noticeable differences were detected across the tested radiation levels. These results support previous findings indicating that gamma irradiation may promote the accumulation of antioxidant compounds in certain plants, including garlic⁴⁶. When cold plasma treatment was applied, higher intensities resulted in greater phenolic content compared to samples treated with gamma radiation. However, extending the duration of cold plasma exposure caused a decline in phenolic compound levels.

The observed increase in phenolic content and antioxidant activity in samples treated with cold plasma at 25 kV for 5 minutes compared to both the 15-minute treatment and the control may be attributed to several factors. These include the possible degradation of phenolic compounds during longer exposure, the presence of sufficient energy for compound generation during shorter treatments, elevated temperatures associated with prolonged plasma application, and time-dependent variations in reactive species activity^{47,48}.

Previous research has demonstrated that cold plasma treatment can enhance the accumulation of phenolic compounds and flavonoids in plant tissues. One proposed explanation is that the UV radiation generated during plasma exposure stimulates the synthesis of phenolic compounds, particularly by affecting the epidermal cells of plant surfaces⁴⁹. On the other hand, a decline in phenolic levels observed with extended plasma exposure may result from compound degradation. This process is believed to begin with the interaction of reactive oxygen species with the plant surface, initiated by random bond disruptions⁵⁰.

Among the evaluated color parameters, the b* value showed notable variation depending on the disinfection method, with observed values ranging from 19.8 to 22.39 across the different treatments. As for the L* and a* indices, the findings are consistent with those of Banerjee, et al.⁵¹, who reported that gamma irradiation did not produce statistically significant alterations in key sensory attributes, including color, aroma, texture, and flavor. Variations in color parameters are often attributed to factors such as plant species and exposure duration, potentially driven by oxidative reactions triggered during processing⁵².

Analysis of essential oils in the treated plants revealed that the applied disinfection methods had a significant impact on both the overall essential oil content and its individual components. Specifically, an increase in gamma radiation intensity corresponded with a notable enhancement in essential oil concentration within the plant tissues. This enhancement could be attributed to the stimulation of metabolic pathways responsible for essential oil biosynthesis triggered by gamma radiation⁵³. Moreover, gamma irradiation may induce structural changes in plant cells, facilitating the release or synthesis of volatile compounds⁵⁴.

The concentrations of dipropyl disulfide (ranging from 15.1% to 18.3%) and d-limonene (between 4.0% and 5.2%) in the essential oils showed a positive correlation with increasing gamma radiation intensity. Similar trends have been documented in previous research, where gamma irradiation enhanced the levels of bioactive compounds in essential oils. For instance, in this study, the cold plasma treatment at 15 kV led to increased levels of sulfur compounds specially dipropyl disulfide, the dominant compound in the essential oil. Sulfur-containing compounds like dipropyl disulfide significantly contribute to the antioxidant and antimicrobial quality of *Allium* vegetables⁵⁵. Our findings show that cold plasma treatment effectively preserves these volatile sulfur compounds by inhibiting microbial growth and reducing oxidative degradation during storage. This preservation helps maintain the nutritional and sensory properties of the vegetables, highlighting cold plasma as a promising postharvest method for quality retention⁵⁶.

The use of various packaging methods was shown to affect both quantitative and qualitative indices of the packaged products. HDPE is an ideal packaging material due to its low permeability to water vapor. It prevents environmental moisture from reaching the product, protecting it from quality degradation. As a result, it helps maintain the product's stability and extends its shelf life⁵⁷. Findings from the present study indicate that both the duration of packaging and the environmental conditions during storage may play a role in modulating the phenolic profile and color characteristics of *A. fistulosum* L. Extended storage periods appeared to be linked with a gradual decline in phenolic content and antioxidant potential⁵⁸, alongside shifts in color indices specifically, an elevation in the a* value and a reduction in the L* value⁵⁹.

Vacuum packaging was associated with a decrease in phenolic compounds and antioxidant activity. Environmental factors including light exposure, temperature fluctuations, and atmospheric gas composition can influence the stability of phenolic compounds over time. Such degradation may be related to the disruption of cellular membranes⁶⁰. These findings show that packaging features like material thickness and permeability play an important role in how quickly gases exchange and how the product breathes⁶¹. Vacuum packaging is essential for improving the quality and shelf life of vegetables like onions. By reducing oxygen exposure, it slows down oxidation and microbial growth that cause spoilage⁶². This method helps preserve important nutrients and antioxidants, maintaining freshness and color. Overall, vacuum packaging is an effective way to keep vegetables fresh longer and enhance their market value⁶³.

The essential oil content varied depending on the packaging type. Specifically, packaging PF4 under normal air conditions resulted in higher essential oil content after 4 and 8 months, whereas packaging PF3 and PF2 under similar conditions showed a decrease in essential oil content after 4 months. Nanocomposite coatings improve shelf life by acting as barriers against moisture and oxygen, reducing spoilage⁶⁴. They often contain antimicrobial nanoparticles that inhibit microbial growth and help control volatile compound release. These coatings also enhance mechanical strength, protecting products during storage and transport.

Especially under vacuum conditions, nanocomposite packaging effectively preserves essential oils and maintains product quality⁶⁵.

The results align with previous studies highlighting the effectiveness of active nanocomposite packaging, especially under vacuum, in reducing oxidation and preserving sensitive compounds. Interaction effects emphasize the coatings' role in minimizing degradation and maintaining essential oil integrity⁶⁶. These findings are important for the pharmaceutical and food industries aiming to extend the shelf life of vegetable essential oils. Moreover, selecting suitable materials and packaging conditions is crucial in horticulture and postharvest handling of vegetables and herbs to preserve quality and prolong shelf life.

Methods

Plant material

Premium dried Welsh onions (*Allium fistulosum* L.) were sourced from local market in the city of Erbil (Iraq). Before the experiments, the plant material was botanically authenticated to confirm its purity.

Disinfection

An experiment employing a completely randomized design with five repetitions was carried out to evaluate different disinfection strategies. The treatments under investigation included gamma radiation and cold plasma. Gamma radiation was administered at levels of 1, 3, and 5 kilogray (kGy), whereas cold plasma was applied at intensities of 15, 20, and 25 kilovolts (kV), each for exposure times of 5, 10, and 15 minutes, accordingly.

Packaging

A factorial experimental design with five replicates was employed to assess the influence of various packaging materials and storage conditions. The study examined two key variables: the type of packaging film-comprising four nanocomposite films with gas barrier properties and the storage time, categorized into three durations: 4, 8, and 12 months. Welsh onion samples were sealed under two packaging environments: atmospheric (A) and vacuum (V), utilizing a locally available packaging system. Throughout the storage period, qualitative characteristics of the plant material were monitored at each designated time point. The physical and structural features of the packaging films are detailed in Table 1.

Total phenolic content

Total phenolic content of *A. fistulosum* L. was measured using the Folin–Ciocalteu method⁶⁷. A standard curve was prepared with methanolic gallic acid solutions (20–1000 µg/mL), mixed with 0.1 mL Folin–Ciocalteu reagent and 0.27 mL of 7.5% sodium carbonate after 3 minutes. Absorbance was recorded at 765 nm after 2 hours at room temperature using a Smart Spec Plus spectrophotometer (Bio-Rad). For analysis, 30 µL of extract (0.05 g/mL) was tested in triplicate. Results were expressed as mg gallic acid equivalents per gram of dry extract (mg GAE/g DW).

Antioxidant Activity

The antioxidant potential of the ethanolic extracts was assessed using the DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging assay, following the procedure described by Bozin, et al.⁶⁸. The results were expressed in terms of IC₅₀ values, which indicate the concentration required to inhibit 50% of the DPPH radicals. Lower IC₅₀ values correspond to higher antioxidant capacity, allowing for a comparative evaluation of the extracts' efficacy.

Color indexes

Color analysis was conducted using samples placed in a 50 × 50 cm lightbox. Images were captured with a Logitech HD Pro Webcam (Model C9020) and processed to extract RGB values using Average Color software. These values were converted to L*, a*, and b* indices using Colormine software, and additional color indices were calculated using specific formulas. The CIE Lab* color model (1976), a global standard for color measurement, was used: L* indicates lightness (0 = black, 100 = white), a* represents the red-green axis (positive = red, negative = green), and b* represents the yellow-blue axis (positive = yellow, negative =

blue). Color changes were also tracked throughout the study using a ColorFlex colorimeter (HunterLab, USA), calibrated with a standard white tile. L*, a*, and b* values were recorded accordingly.

Essential oil content and composition

A total of 100 g of dried, powdered plant material was subjected to hydro-distillation with 1500 mL of distilled water for 4 hours using a Clevenger-type apparatus. The extracted essential oil (EO) was dried over anhydrous sodium sulfate and stored in dark vials at 4 °C ⁶⁹. For chemical analysis, the EO was analyzed using GC-MS (Agilent 5973, USA) equipped with an HP-5MS capillary column (30 m length, 0.25 mm internal diameter, 0.25 µm film thickness). The column temperature was programmed to start at 70 °C (2 min hold), increase at 15 °C/min to 220 °C, and then rise to 300 °C with a 2 min hold. The injector temperature was 290 °C, and helium served as the carrier gas at 0.8 mL/min. The ion source temperature was 220 °C with 70 eV ionization energy ⁷⁰. EO yield was calculated as the percentage of oil extracted relative to the plant's dry weight.

Statistical analysis

Data were analyzed using a completely randomized design (CRD) with five replicates. Analysis of variance (ANOVA) was conducted using SAS software (version 9.0). Normality of residuals was verified with the PROC UNIVARIATE procedure. Mean comparisons were performed using the least significant difference (LSD) test at a 5% significance level.

Conclusion

This study demonstrated that disinfection methods, packaging, and storage duration significantly affect the phenolic content, antioxidant activity, color, and essential oil composition of the vegetable *Allium fistulosum* L. (Welsh onion). Cold plasma treatment, especially at 25 kV for 5 minutes, was the most effective in preserving and enhancing bioactive compounds, while high-dose gamma irradiation reduced these qualities. Packaging methods also influenced quality retention, with certain treatments like PF₃A better maintaining phenolics and essential oils, though overall quality declined over longer storage. Vacuum packaging notably affected sulfur-containing compounds in the essential oils. Given the importance of quality and shelf-life in horticultural products, cold plasma combined with appropriate packaging offers a promising non-thermal technology to extend freshness and preserve the functional properties of fresh vegetables like Welsh onion.

Declarations

Conflict of interest statement

The authors report that there are no competing interests to declare.

Author's contribution statement

R.G., A.A.A., and A.K.K. designed the study. S.O., and S.SH. performed the field and laboratory experiments. F.F. and M.N. performed Methodology. M.B.A., J.K.A., and H.F.H. analyzed the data. R.G., A.A.A., and A.K.K. wrote the paper with input from all authors.

Data availability

Data are available from the corresponding author and the first author upon reasonable request.

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Tables

Table 1. Structural characteristics of the packaging films

Names	Components (%)		
	High Density Polyethylene (HB0035)	Compatibilizer (Maleic anhydride-grafted polypropylene)	Nano Clay (Cloisite 15A)
PF ₁	90.0	7.5	2.5
PF ₂	90.0	5.0	5.0
PF ₃	95.0	0.0	5.0
PF ₄	85.0	7.5	7.5

Table 2. Abbreviations and their definitions

Abbreviations	Descriptions
PF ₁ A	(CISA _{2.5} -ppgMA _{7.5} -HDPE _{90.0} + normal air)
PF ₁ V	(CISA _{2.5} -ppgMA _{7.5} -HDPE _{90.0} + vacuum)
PF ₂ A	(CISA _{5.0} -ppgMA _{5.0} -HDPE _{90.0} + normal air)
PF ₂ V	(CISA _{5.0} -ppgMA _{5.0} -HDPE _{90.0} + vacuum)
PF ₃ A	(CISA _{5.0} -ppgMA _{0.0} -HDPE _{95.0} + normal air)
PF ₃ V	(CISA _{5.0} -ppgMA _{0.0} -HDPE _{95.0} + vacuum)
PF ₄ A	(CISA _{7.5} -ppgMA _{7.5} -HDPE _{85.0} + normal air)
PF ₄ V	(CISA _{5.7} -ppgMA _{0.0} - EVA _{5.0} -HDPE _{87.5} + vacuum)

Table 3. Effect of different disinfection treatments on L*, a* and b* index

Disinfection	L*	a*	b*
Control	62.27 ^a	4.26 ^a	22.39^a
Gamma 1 KGy	61.58 ^a	4.59 ^a	20.03 ^b
Gamma 3 KGy	62.18 ^a	4.63^a	19.95 ^b
Gamma 5 KGy	61.01 ^a	4.61 ^a	19.80 ^b
Cold plasma, 15 KV, 5 min	61.74 ^a	4.40 ^a	19.80 ^b
Cold plasma, 15 KV, 10 min	61.15 ^a	4.21 ^a	20.64 ^b
Cold plasma, 15 KV, 15 min	61.51 ^a	4.26 ^a	20.78 ^b
Cold plasma, 20 KV, 5 min	61.67 ^a	4.18 ^a	20.28 ^b
Cold plasma, 20 KV, 10 min	62.37^a	4.55 ^a	20.66 ^b
Cold plasma, 20 KV, 15 min	60.69 ^a	4.12 ^a	19.80 ^b
Cold plasma, 25 KV, 5 min	61.31 ^a	4.10 ^a	20.69 ^b
Cold plasma, 25 KV, 10 min	60.61 ^a	4.06 ^a	21.89^a
Cold plasma, 25 KV, 15 min	61.60 ^a	4.63^a	19.89 ^b

The presence of at least one similar letter in each column indicates no significant difference based on the LSD test ($P \leq 0.05$).

Table 4. Essential oil analysis of samples treated with different methods of disinfection

Compounds		RI*	Gamma irradiation			Cold plasma								
			1	3	5	15 KV			20 KV			25 KV		
No			KGy	KGy	KGy	5 min	10 min	15 min	5 min	10 min	15 min	5 min	10 min	15 min
1	Dimethyl disulfide	736	0.5	0.4	0.3	0.2	0.2	0.4	-	-	-	-	-	-
2	2-Methyl-2-pentenal	820	3.2	2.8	3.1	2.8	2.5	0.7	2.1	2.2	2.6	2.9	2.5	3.5
3	2,4-Dimethylthiophene	887	0.4	-	0.1	0.2	0.6	0.4	0.3	0.4	0.4	0.3	0.3	0.3
4	Methyl propyl disulfide	904	3.7	3.9	2.7	3.1	3.2	2.8	3.3	3.6	3.8	3.1	4.2	3.7
5	Dimethyl trisulfide	952	9.2	11.1	11.0	8.2	8.6	8.5	8.1	7.9	8.1	7.7	6.6	6.3
6	D-limonene	1020	4.0	5.1	5.2	7.2	7.3	8.7	7.3	6.4	6.5	5.1	5.2	5.2
7	Diallyl disulphide	1056	10.0	8.5	8.2	10.4	10.9	10.9	11.1	11.3	11.4	9.7	9.5	8.2
8	(E)-Propenyl-2-propyl disulfane	1067	4.5	4.2	5.3	2.5	3.4	5.3	5.2	5.1	4.5	5.1	4.8	4.7
9	Dipropyl disulfide	1094	15.1	15.4	18.3	16.0	17.2	17.2	17.2	16.2	15.3	15.2	15.0	13.2
10	(E)-Methyl-2-propenyl disulfane	1110	0.5	1.1	1.1	0.5	-	-	0.3	0.2	0.5	0.3	0.3	0.4
11	Methyl propyl trisulfide	1152	10.0	8.4	8.1	13.1	11.4	12.5	11.3	11.3	11.3	9.4	9.3	9.2
12	(E)-1 -Propenyl methyl trisulfide	1172	1.0	2.1	1.2	1.1	1.3	2.1	2.1	2.1	2.7	1.2	1.2	1.3
13	Dimethyl tetrasulfide	1234	0.5	0.7	0.5	0.5	0.7	0.7	0.7	0.6	0.6	0.5	0.7	0.5
14	Dipropyl trisulfide	1313	10.0	12.2	10.3	11.3	10.7	10.9	12.3	13.0	11.5	10.3	10.0	9.7
15	1,2,4-Trithiolane, 3,5-diethyl	1322	5.9	5.4	5.4	4.4	5.2	4.4	4.5	4.3	4.7	5.1	6.1	5.8
16	Propyl 2-propenyl trisulfide	1410	1.7	1.4	2.1	0.9	0.9	0.8	0.5	0.5	0.6	0.8	0.6	0.6
17	Phenol, 3-methyl-4-(methylthio)	1416	2.5	2.8	1.9	1.5	1.4	1.1	1.0	1.4	2.1	2.9	2.0	2.1
18	2-Dodecanol	1458	2.7	3.1	3.1	2.0	3.1	2.1	2.0	3.1	3.1	4.1	4.5	6.1
19	Acetic acid, trimethylsilyl ester	1600	0.8	0.7	1.0	0.5	0.7	0.3	0.5	0.3	0.4	0.1	1.1	1.8
20	2-Tridecanone	1692	1.5	2.9	2.1	1.4	1.4	1.1	1.4	1.6	2.6	2.7	2.3	3.2
21	Dipropyl tetrasulfide	1762	1.2	1.2	1.3	1.1	1.2	1.5	1.4	1.5	1.6	1.8	1.9	2.2
22	Propyl 2-propenyl tetrasulfide	1778	3.8	3.4	3.3	3.3	3.4	3.3	2.2	2.3	3.3	4.3	4.2	3.9
23	(E)-1 -Propenyl propyl tetrasulfide	1811	0.3	-	-	0.4	0.2	0.4	0.5	0.6	0.6	0.5	0.5	0.6
24	(E)-1-Propenyl propyl	2121	0.1	0.2	0.2	0.3	0.2	0.1	0.1	0.2	0.2	0.3	0.2	0.3

pentasulfide														
25	Palmitic acid	2322	0.4	0.6	0.7	1.2	0.5	0.3	0.3	0.5	0.5	0.7	0.7	0.6
	Total sulfur-containing compounds		85.7	85.0	87.5	87.7	89.7	92.3	89.9	89.2	89.2	83.7	83.7	80.0
	Total	-	95.5	94.4	96.5	99.1	97.2	96.5	95.7	96.6	98.0	94.1	93.7	88.7

*RI: calculated retention indices according to the homologous normal alkanes (C8-C24)

Table 5. Packaging × storage period interaction on the color characteristics (L*, a* and b* index)

Packaging	Storage period (months)	L*	a*	b*
PF1A	4	53.0^a	8.2 ^b	26.6 ^b
	8	50.7 ^b	8.1 ^b	26.6 ^b
	12	48.5 ^c	8.2 ^b	26.2 ^b
PF1V	4	52.6 ^{ab}	8.1 ^b	26.3 ^b
	8	50.0 ^b	8.3 ^b	26.2 ^b
	12	47.7 ^c	8.5 ^b	26.4 ^b
PF2A	4	51.5 ^b	7.9 ^b	26.2 ^b
	8	49.6 ^{bc}	8.0 ^b	26.4 ^b
	12	47.0 ^c	9.4^a	26.1 ^b
PF2V	4	51.6 ^b	8.2 ^b	26.5 ^b
	8	49.6 ^{bc}	8.2 ^b	26.4 ^b
	12	46.3 ^{cd}	9.3^a	26.7 ^b
PF3A	4	52.2 ^{ab}	8.2 ^b	26.9 ^b
	8	50.0 ^b	7.8 ^b	27.4 ^b
	12	47.5 ^c	7.6 ^b	26.7 ^b
PF3V	4	50.7 ^b	7.9 ^b	26.5 ^b
	8	48.8 ^c	8.0 ^b	27.0 ^b
	12	45.5 ^{cd}	9.7^a	26.1 ^b
PF4A	4	52.7 ^{ab}	8.7 ^b	26.3 ^b
	8	50.3 ^b	7.9 ^b	26.5 ^b
	12	47.5 ^c	8.0 ^b	25.2 ^b
PF4V	4	52.4 ^{ab}	8.0 ^b	26.4 ^b
	8	49.2 ^{bc}	8.0 ^b	26.3 ^b
	12	46.9 ^c	7.4 ^b	30.8^a

The presence of at least one similar letter in each column indicates no significant difference based on the LSD test ($P \leq 0.05$).

PF1A: CISA2.5-ppgMA7.5-HDPE90.0 + normal air, PF1V: CISA2.5-ppgMA7.5-HDPE90.0 + vacuum, PF2A: CISA5.0-ppgMA5.0-HDPE90.0+ normal air, PF2V: CISA5.0-ppgMA5.0-HDPE90.0+ vacuum, PF3A: CISA5.0-ppgMA0.0-HDPE95.0+ normal air, PF3V: CISA5.0-ppgMA0.0-HDPE95.0+ vacuum, PF4A: CISA7.5-ppgMA7.5HDPE85.0+ normal air, PF4V: CISA5.7-ppgMA0.0- EVA5.0-HDPE87.5 + vacuum.

Table 6. Composition of essential oil under PF₁A and PF₁V treatments

No	Compounds	RI*	PF ₁ A			PF ₁ V		
			4	8	12	4	8	12
1	Dimethyl disulfide	736	0.5	0.3	0.4	0.7	0.3	1.2
2	2-Methyl-2-pentenal	820	1.2	1.3	1.5	1.2	1.3	3.4
3	2,4-Dimethylthiophene	887	0.4	0.8	0.9	1.5	1.9	2.0
4	Methyl propyl disulfide	904	3.7	4.0	3.6	3.6	3.9	10.8
5	Dimethyl trisulfide	952	9.2	9.9	7.8	10.5	9.8	7.3
6	D-limonene	1020	4.0	5.1	4.1	7.3	7.1	5.1
7	Diallyl disulphide	1056	10.0	9.2	8.2	7.6	7.3	6.8
8	(E)-Propenyl-2-propyl disulfane	1067	4.5	7.5	13.3	4.8	2.4	3.7
9	Dipropyl disulfide	1094	15.1	16.3	16.1	15.3	14.8	10.4
10	(E)-Methyl-2-propenyl disulfane	1110	0.5	0.1	0.1	0.2	0.1	0.3
11	Methyl propyl trisulfide	1152	10.0	9.2	8.1	9.3	9.4	8.8
12	(E)-1 -propenyl methyl trisulfide	1172	1.0	0.1	0.1	-	-	-
13	Dimethyl tetrasulfide	1234	0.5	0.6	0.3	0.7	0.4	0.5
14	Dipropyl trisulfide	1313	12.0	11.9	12.4	12.7	13.4	13.0
15	1,2,4-Trithiolane, 3,5-diethyl	1322	5.9	5.6	5.3	6.2	5.2	5.1
16	Propyl 2-propenyl trisulfide	1410	1.7	2.2	2.1	1.1	1.0	0.9
17	Phenol, 3-methyl-4-(methylthio)	1416	2.5	1.3	1.5	1.4	0.5	0.3
18	2-Dodecanol	1458	2.7	3.1	1.9	3.1	2.2	2.7
19	Acetic acid, trimethylsilyl ester	1600	0.8	0.9	1.1	0.8	0.8	0.6
20	2-Tridecanone	1692	2.5	2.9	2.8	3.1	3.0	3.2
21	Dipropyl tetrasulfide	1762	1.2	1.3	1.0	2.3	3.2	2.6
22	Propyl 2-propenyl tetrasulfide	1778	3.8	2.7	3.2	3.1	2.9	2.6
23	(E)-1 -propenyl propyl tetrasulfide	1811	0.3	0.3	0.5	0.4	0.1	0.2
24	(E)-1-propenyl propyl pentasulfide	2121	0.1	-	-	0.1	0.1	0.1
25	Palmitic acid	2322	0.4	0.5	0.6	0.7	0.7	0.9
Total sulfur-containing compounds			82.9	83.3	84.9	81.5	76.7	76.6
Total			94.5	97.3	96.8	97.7	91.4	92.5

*RI: calculated retention indices according to the homologous normal alkanes (C8-C24)

PF₁A: CISA_{2.5}-ppgMA_{7.5}-HDPE_{90.0} + normal air, PF₁V: CISA_{2.5}-ppgMA_{7.5}-HDPE_{90.0} + vacuum

Table 7. Composition of essential oil under PF₂A and PF₂V treatment

Compounds		RI*	PF ₂ A			PF ₂ V		
No			4	8	12	4	8	12
	Dimethyl disulfide	736	0.7	0.7	0.6	0.6	0.4	0.2
1	2-Methyl-2-pentenal	820	1.7	2.5	3.1	1.7	1.5	1.7
2	2,4-Dimethylthiophene	887	0.4	0.7	0.3	0.7	0.5	0.4
3	Methyl propyl disulfide	904	3.3	3.7	3.1	2.6	1.9	1.8
4	Dimethyl trisulfide	952	7.1	7.2	8.8	6.5	5.9	5.3
5	D-limonene	1020	7.3	7.1	5.2	6.9	6.1	7.1
6	Diallyl disulphide	1056	9.2	9.2	8.2	8.5	8.3	6.9
7	(<i>E</i>)-Propenyl-2-propyl disulfane	1067	4.7	4.5	3.3	4.8	4.4	3.9
8	Dipropyl disulfide	1094	10.9	10.3	10.1	11.3	10.8	10.0
9	(<i>E</i>)-Methyl-2-propenyl disulfane	1110	0.3	0.3	0.2	0.5	0.2	0.3
10	Methyl propyl trisulfide	1152	13.3	13.2	13.1	14.3	13.2	11.1
11	(<i>E</i>)-1 -propenyl methyl trisulfide	1172	1.0	1.2	1.0	0.8	1.0	0.8
12	Dimethyl tetrasulfide	1234	0.5	0.4	0.4	0.6	0.4	0.5
13	Dipropyl trisulfide	1313	11.0	9.9	9.4	10.7	10.4	10.0
14	1,2,4-Trithiolane, 3,5-diethyl	1322	5.0	3.6	4.3	5.2	5.2	5.0
15	Propyl 2-propenyl trisulfide	1410	1.0	0.7	0.1	0.4	0.4	0.2
16	Phenol, 3-methyl-4-(methylthio)	1416	2.9	3.3	3.5	3.4	1.5	1.3
17	2-Dodecanol	1458	2.0	1.1	2.4	5.1	4.2	3.9
18	Acetic acid, trimethylsilyl ester	1600	1.3	1.2	1.1	0.8	2.5	2.6
19	2-Tridecanone	1692	3.1	2.8	3.1	3.1	3.2	3.0
20	Dipropyl tetrasulfide	1762	1.4	1.1	1.0	1.3	1.1	0.6
21	Propyl 2-propenyl tetrasulfide	1778	3.1	2.9	2.2	3.3	2.5	2.6
22	(<i>E</i>)-1 -propenyl propyl tetrasulfide	1811	0.4	0.3	0.2	0.4	0.4	0.3
23	(<i>E</i>)-1-propenyl propyl pentasulfide	2121	0.1	0.2	0.1	0.1	0.1	-
24	palmitic acid	2322	0.7	0.5	0.6	0.7	0.5	0.5
25	Total sulfur-containing compounds		76.3	73.4	69.9	76.0	68.6	61.2
	Total		92.4	88.6	85.4	94.3	87.6	80.0

*RI: calculated retention indices according to the homologous normal alkanes (C8-C24)

PF₂A: CISA_{5.0}-ppgMA_{5.0}-HDPE_{90.0}+ normal air, PF₂V: CISA_{5.0}-ppgMA_{5.0}-HDPE_{90.0}+ vacuum

Table 8. Composition of essential oil under PF₃A and PF₃V treatment

No	Compounds	RI*	PF ₃ A			PF ₃ V		
			4	8	12	4	8	12
1	Dimethyl disulfide	736	0.5	0.3	0.3	0.6	0.4	0.5
2	2-Methyl-2-pentenal	820	1.2	0.9	1.2	3.5	4.8	4.6
3	2,4-Dimethylthiophene	887	0.4	0.6	0.8	1.2	1.1	1.0
4	Methyl propyl disulfide	904	3.7	2.9	3.9	5.4	5.2	4.9
5	Dimethyl trisulfide	952	8.2	8.6	7.8	7.2	6.9	6.5
6	D-limonene	1020	7.0	8.2	9.1	8.9	8.2	8.2
7	Diallyl disulphide	1056	9.0	8.1	7.2	7.4	7.3	7.2
8	(<i>E</i>)-Propenyl-2-propyl disulfane	1067	4.5	4.0	3.9	3.5	4.3	3.0
9	Dipropyl disulfide	1094	14.5	14.2	13.2	10.2	9.2	9.0
10	(<i>E</i>)-Methyl-2-propenyl disulfane	1110	0.5	0.4	0.5	0.4	0.5	0.2
11	Methyl propyl trisulfide	1152	12.0	10.1	9.1	8.1	8.3	8.2
12	(<i>E</i>)-1 -propenyl methyl trisulfide	1172	1.0	1.1	1.1	1.0	1.1	0.9
13	Dimethyl tetrasulfide	1234	0.5	0.6	0.5	0.4	0.6	0.5
14	Dipropyl trisulfide	1313	15.0	14.3	14.9	13.2	13.1	12.8
15	1,2,4-Trithiolane, 3,5-diethyl	1322	5.9	5.3	5.1	6.1	6.1	8.1
16	Propyl 2-propenyl trisulfide	1410	1.7	1.1	1.1	1.1	1.0	0.8
17	Phenol, 3-methyl-4-(methylthio)	1416	2.5	3.5	2.3	2.3	2.9	3.2
18	2-Dodecanol	1458	2.7	3.1	4.5	3.1	3.0	3.1
19	Acetic acid, trimethylsilyl ester	1600	0.8	0.7	0.9	0.5	0.6	0.7
20	2-Tridecanone	1692	1.5	1.8	2.5	2.1	3.5	3.9
21	Dipropyl tetrasulfide	1762	1.2	0.9	0.3	0.5	0.5	0.3
22	Propyl 2-propenyl tetrasulfide	1778	3.8	3.1	2.4	3.1	2.2	2.2
23	(<i>E</i>)-1 -propenyl propyl tetrasulfide	1811	0.3	0.3	0.3	0.4	0.4	0.3
24	(<i>E</i>)-1-propenyl propyl pentasulfide	2121	0.1	0.1	0.1	-	-	-
25	Palmitic acid	2322	0.4	0.6	0.6	0.4	0.1	-
Total sulfur-containing compounds			85.3	79.5	74.8	72.1	71.1	69.6
Total			98.9	95.1	93.8	90.6	91.3	90.1

*RI: calculated retention indices according to the homologous normal alkanes (C8-C24)

PF₃A: CISA_{5,0}-ppgMA_{0,0}-HDPE_{95,0}+ normal air, PF₃V: CISA_{5,0}-ppgMA_{0,0}-HDPE_{95,0}+ vacuum

Table 9. Composition of essential oil under PF₄A and PF₄V treatment

No	Compounds	RI*	PF ₄ A			PF ₄ V		
			4	8	12	4	8	12
1	Dimethyl disulfide	736	0.5	0.4	0.5	0.4	0.4	0.2
2	2-Methyl-2-pentenal	820	1.1	0.8	0.8	1.1	1.0	1.3
3	2,4-dimethylthiophene	887	0.3	0.5	0.3	0.5	0.2	0.8
4	Methyl propyl disulfide	904	2.9	2.8	1.8	3.5	2.0	2.6
5	Dimethyl trisulfide	952	9.1	8.4	8.3	8.8	7.0	7.7
6	D-limonene	1020	5.2	5.1	4.1	6.1	6.2	7.2
7	Diallyl disulphide	1056	8.1	9.0	10.3	10.3	10.7	9.6
8	(<i>E</i>)-Propenyl-2-propyl disulfane	1067	3.9	2.5	1.8	6.0	4.9	4.3
9	Dipropyl disulfide	1094	12.9	11.2	10.5	14.3	10.3	10.2
10	(<i>E</i>)-Methyl-2-propenyl disulfane	1110	0.2	0.3	0.2	0.1	0.2	0.3
11	Methyl propyl trisulfide	1152	10.3	9.1	9.9	10.1	9.3	10.2
12	(<i>E</i>)-1 -propenyl methyl trisulfide	1172	1.5	2.0	2.1	2.2	2.0	1.1
13	Dimethyl tetrasulfide	1234	0.7	1.0	0.6	0.9	0.7	0.6
14	Dipropyl trisulfide	1313	15.3	15.3	15.8	16.4	15.9	15.0
15	1,2,4-Trithiolane, 3,5-diethyl	1322	5.5	5.1	5.2	6.2	5.0	5.7
16	Propyl 2-propenyl trisulfide	1410	1.1	0.9	0.2	0.9	0.5	0.6
17	Phenol, 3-methyl-4-(methylthio)	1416	2.4	2.7	2.1	2.8	2.7	1.4
18	2-Dodecanol	1458	2.7	3.1	2.9	2.2	1.1	0.5
19	Acetic acid, trimethylsilyl ester	1600	0.5	0.5	0.8	0.7	0.5	0.1
20	2-Tridecanone	1692	2.4	2.1	1.9	1.5	1.1	2.8
21	Dipropyl tetrasulfide	1762	1.0	1.0	1.1	0.3	0.5	0.1
22	Propyl 2-propenyl tetrasulfide	1778	3.1	3.1	2.7	1.6	2.4	3.3
23	(<i>E</i>)-1 -propenyl propyl tetrasulfide	1811	0.1	0.2	0.3	0.4	0.3	0.2
24	(<i>E</i>)-1-propenyl propyl pentasulfide	2121	0.2	0.1	0.1	0.5	0.2	0.2
25	Palmitic acid	2322	0.5	0.3	0.4	1.0	0.4	0.2
Total sulfur-containing compounds			79.1	75.6	73.8	86.2	75.2	74.1
Total			92.5	87.5	83.0	98.8	90.0	84.4

*RI: calculated retention indices according to the homologous normal alkanes (C8-C24)

PF₄A: CISA_{7.5}-ppgMA_{7.5}-HDPE_{85.0}+ normal air, PF₄V: CISA_{5.7}-ppgMA_{0.0}- EVA_{5.0}-HDPE_{87.5}+ vacuum

Figures

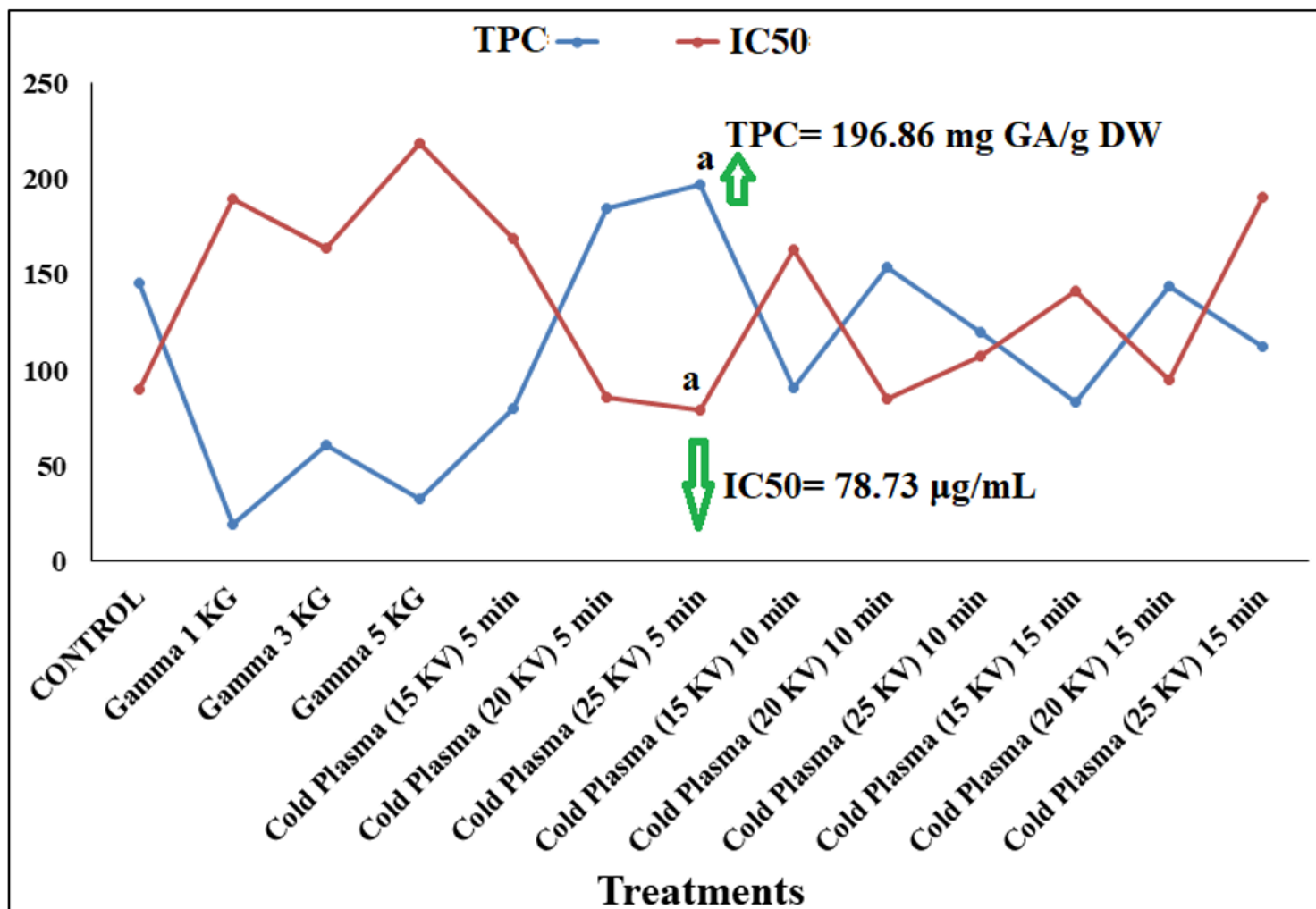


Figure 1

Effect of different disinfection treatments on total phenolic content (TPC) and antioxidant Activity (IC₅₀).

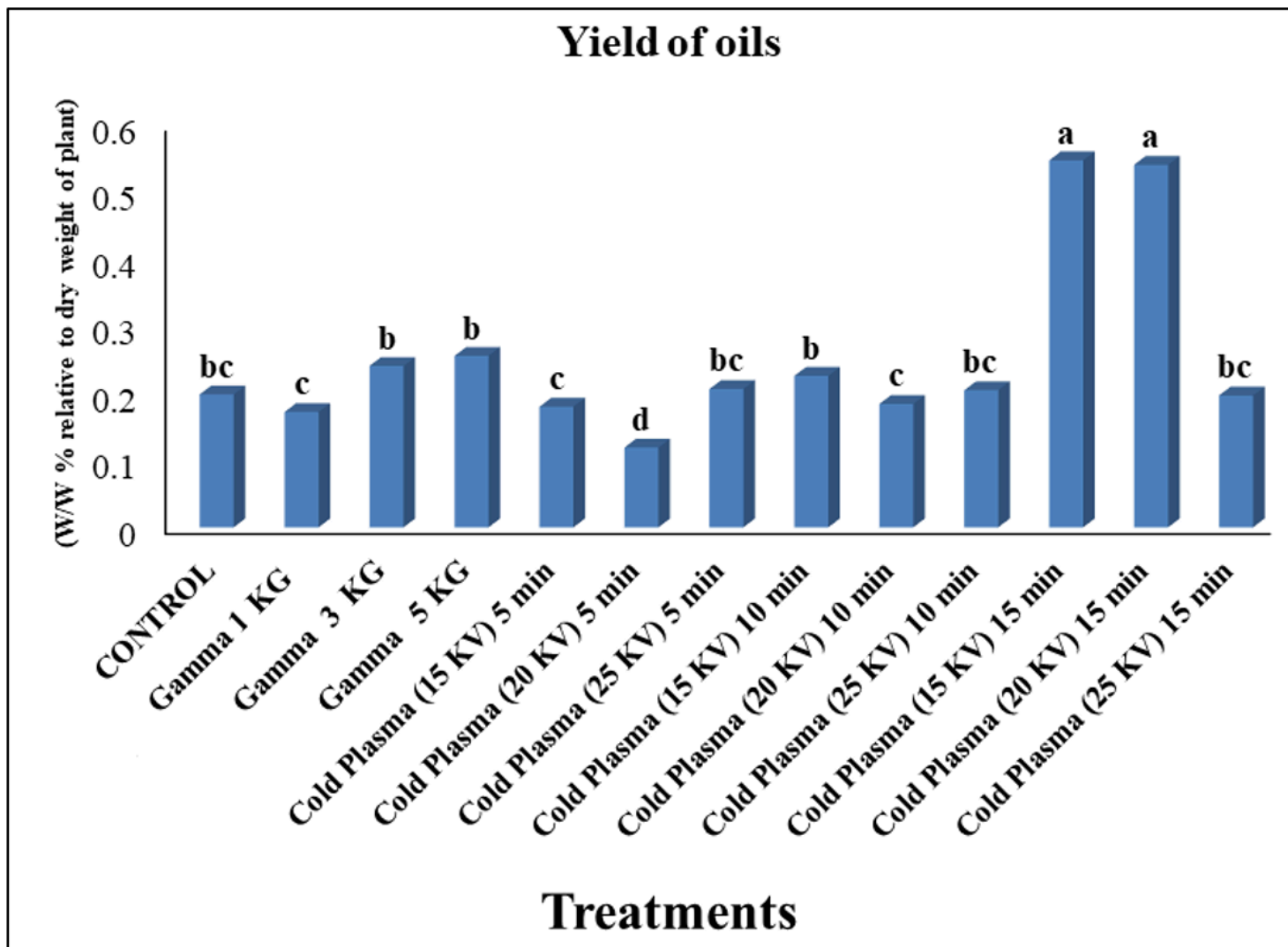


Figure 2

Effect of different disinfection methods on essential oil content (%)

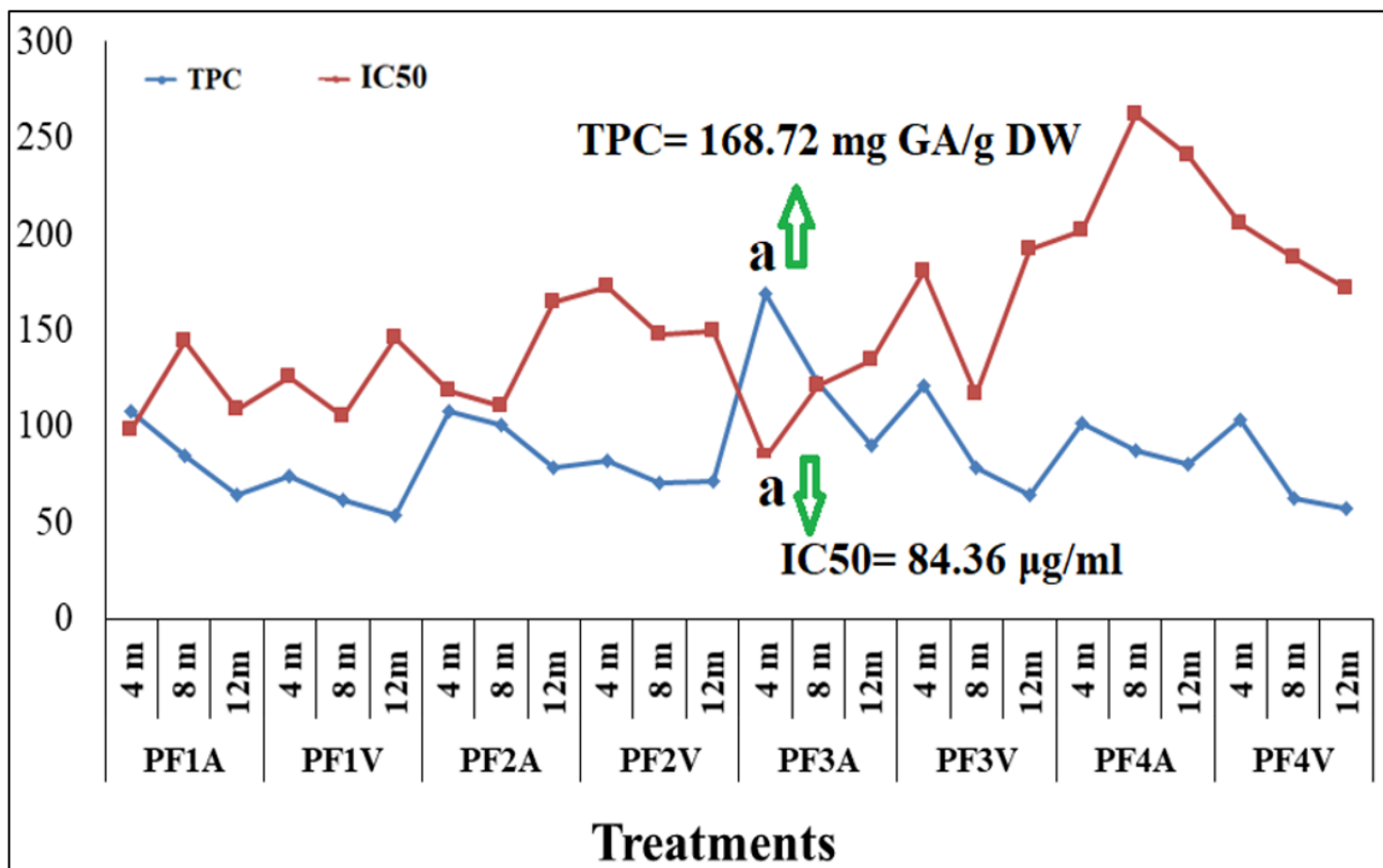


Figure 3

Packaging $\times$ storage period interaction on the total phenolic content (TPC) and antioxidant Activity (IC₅₀)

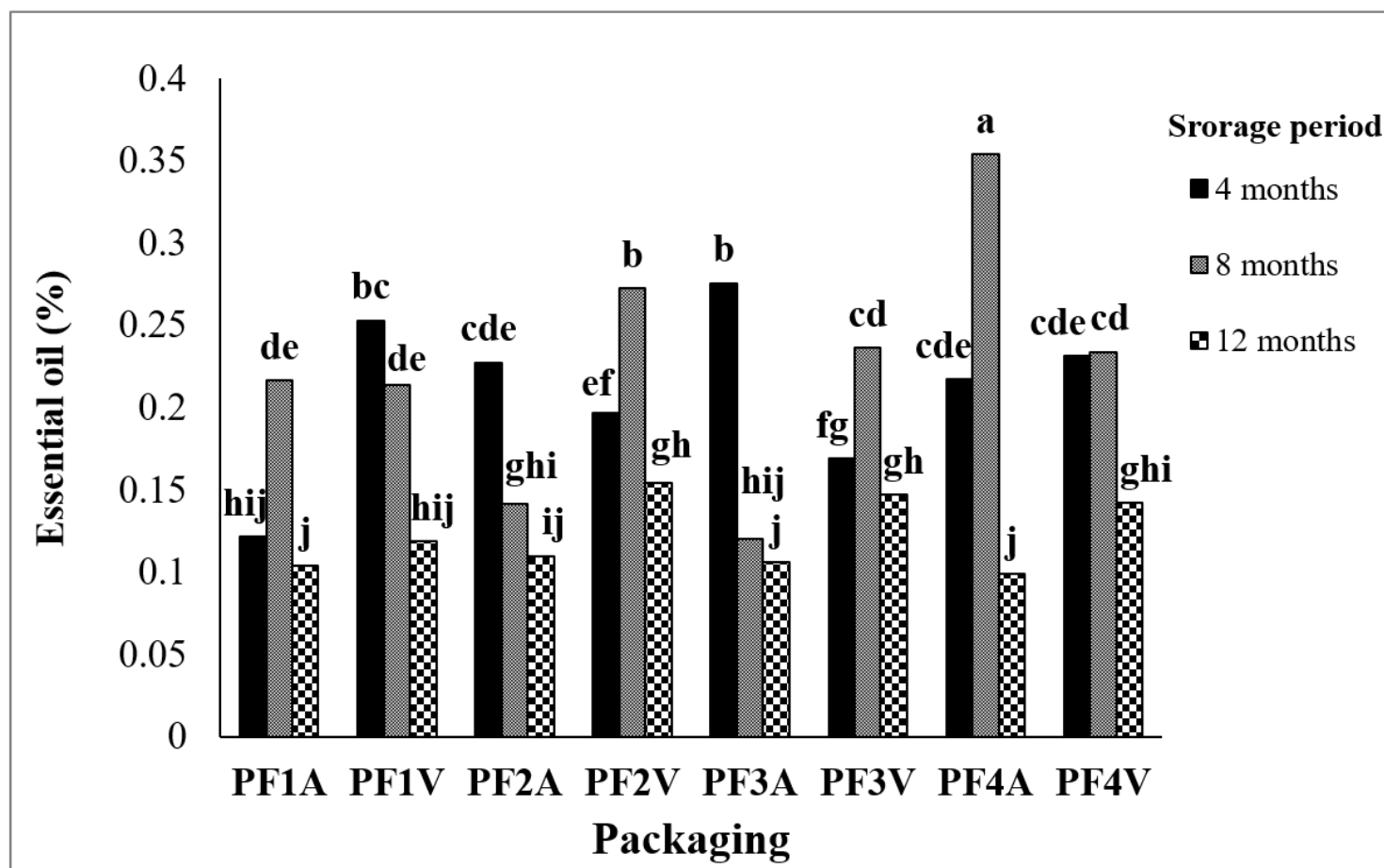


Figure 4

Effect of packaging × storage period on essential oil content (A: Air, V: Vacuum) PF1A: CISA_{2.5}-ppgMA_{7.5}-HDPE_{90.0} + normal air, PF1V: CISA_{2.5}-ppgMA_{7.5}-HDPE_{90.0} + vacuum, PF2A: CISA_{5.0}-ppgMA_{5.0}-HDPE_{90.0} + normal air, PF2V: CISA_{5.0}-ppgMA_{5.0}-HDPE_{90.0} + vacuum, PF3A: CISA_{5.0}-ppgMA_{0.0}-HDPE_{95.0} + normal air, PF3V: CISA_{5.0}-ppgMA_{0.0}-HDPE_{95.0} + vacuum, PF4A: CISA_{7.5}-ppgMA_{7.5}-HDPE_{85.0} + normal air, PF4V: CISA_{5.7}-ppgMA_{0.0}-EVA_{5.0}-HDPE_{87.5} + vacuum.