EFFECT OF THE COMBINED TREATMENT OF UV-C LIGHT AND MODIFIED ATMOSPHERE PACKAGING ON THE INACTIVATION OF *ESCHERICHIA COLI* INOCULATED WATERCRESS

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ABSTRACT

Minimally processed watercress is an alternative to increase vegetable consumption. However, at almost all stages from field production to processing the vegetables could be contaminated with pathogenic and spoilage bacteria. UV-C light can be effective in controlling bacterial growth, but limited information is available for watercress sanitation and storability. This study reports the effect of UV-C light ($0–25$ kJ/m^2) on the quality of minimally processed watercress inoculated with a nonpathogenic *Escherichia coli* (ATCC 35218), and stored under active modified atmosphere (5% O_2–10% CO_2) during 12 days at 5C. The application of UV-C treatments reduced *E. coli* counts between 2.6 and 4.4 log cfu/g. Moreover, the application of $15–25$ kJ/m^2 increased the phenolic content and caused slight changes in the visual appearance and color. Therefore, high UV-C doses could be an effective tool to decrease bacterial growth and to extend shelf life of minimally processed watercress.

PRACTICAL APPLICATIONS

This technology represents an economic alternative compared to other sanitation techniques because of the low costs of the infrastructure and maintaining activities. There are no legal restrictions for UV-C application. The beneficial effects on fruit and vegetable quality make this technology an interesting alternative to extend the postharvest shelf life of minimally processed products. Nowadays, the food market is challenging an increasing demand for safer products elaborated under strict environmental and friendly standards. In this sense, the UV-C technology could be an alternative to chemical sanitation that is being questioned because of the formation of potentially toxic compounds. The successful application depends on the selection of doses that delay microbial growth without causing detrimental effects. Before commercial implementation, a systematic research on the effects of UV-C light in several species is required by evaluating and optimizing the effects of this technology on the overall quality of different vegetables.

INTRODUCTION

Fruit and vegetables are positioned in the market by their recognized functional properties providing substances such as vitamins, minerals, fiber, antioxidant compounds, glucosinolates and phytosterols (Slavin and Lloyd 2012).

The new demands for different food products, the changes in lifestyles and need to reduce the time to prepare healthy meals have led to increase minimally processed (MP) fruit and vegetable demand (Oms-Oliu *et al.* 2010). Fruits and vegetables processed by washing, cutting, rinsing and packaging are well known as MP products, which can

be eaten directly by the consumers. In general, these products keep a freshly appearance for 7 to 14 days under cold storage (Rojas-Graü *et al.* 2009). In order to reduce mechanical damage caused by minimal processing, cold temperatures and modified atmosphere packaging (MAP) techniques are used. These technologies may delay spoilage of the product caused by microorganism and elevated metabolic activity (Gil *et al.* 2006). Enzymes and substrates, separated in different cellular organels inside the cells lose their compartmentalization after cutting allowing chemical reactions among enzymes and substrates. One of these processes is polyphenol oxidase (PPO)-mediated browning, which is exacerbated in processed commodities. These MP products are not free from contamination; for this reason, it is important to assure the product quality (Gil *et al.* 2009). Also, during cutting and processing, the product surface is exposed to air and possible contamination with bacteria, yeasts and molds. Improper handling during the industrial process of these products increases the chance of contamination with pathogens such as *Escherichia coli*, *Listeria*, *Salmonella* and *Yersinia* (Harris *et al.* 2003). Sodium hypochlorite (NaClO) is usually applied as sanitizing treatment to decrease microbial contamination on vegetables. However, it could react with organic matter resulting in chlorine gas, chloramines and trihalomethane formation with potential carcinogenicity effects (Artés *et al.* 2009).

There is great interest in the development of novel sanitation techniques, such as UV-C radiation. The sanitizing effect of UV-C radiation is attributed to the formation of pyrimidine dimers that distort the double helix of DNA by blocking replication process of bacteria, viruses and other pathogens. Also, the DNA helix composition could determine the microbial sensitivity, and the ability to repair the damaged DNA (Gayán *et al.* 2011). Sensitivity to UV-C radiation significantly varies within microorganisms being gram-negative more sensitive than gram-positive bacteria. The different sensitivity has been attributed in part to variation in cell envelopes, which would result in different penetration of the germicide radiation. Microorganisms may differ in their ability to repair damaged DNA. UV-C has been evaluated to delay senescence in commodities like tomato, lettuce and spinach (Baka *et al.* 1999). However, excessive UV-C doses on the products could alter the permeability of the plasma membrane by increasing the leakage of amino acids and carbohydrates and other small nutritive molecules that would favor microbial growth (Guerrero-Beltrán and Barbosa-Cánovas 2004). Treatments with UV-C light offer several advantages to the food industry. It leaves no residue, has no legal restrictions, it is lethal against a large number of microorganisms and has a low cost (Bintsis *et al.* 2000). Guan *et al.* (2012) showed that UV-C doses of 0.45–3.15 kJ/m^2 resulted in 0.67–1.13 log

cfu/g reduction of *E. coli* O157:H7 on mushroom stored for 21 days at 4C. Erkan *et al.* (2001) observed that the UV-C light reduced microbial contamination and deterioration of sliced Italian squash (*Cucurbita pepo* L., cv. Tigress) during storage at 5 and 10C. Also a pretreatment of 2.27 kJ/m^2 reduced aerobic plate counts and *Enterobacteriaceae* in organic pepper strips for 12 days at 5C (Artés *et al.* 2006). In lettuce "Oak leaf" MP, it was found that doses of 1.18, 2.37 and 7.11 kJ/m^2 were effective at reducing the microorganisms causing deterioration after 10 days at 5C, although the dose 7.11 kJ/m^2 caused softening and browning of tissues after 7 days (Allende *et al.* 2006). Furthermore, treatments using UV-C light as an alternative technology would be able to reduce the ripening rate and activate natural defense responses to increase the shelf life of fruit and vegetables (Cuvi *et al.* 2011).

Watercress is demanded by the consumer because of typical mustard flavor and attractive fresh appearance (Gonçalves *et al.* 2009). Little technical information related to sanitation and storability of this vegetable is published. Therefore, the purpose of this study was to evaluate the UV-C light effect on quality parameters of MP watercress inoculated with *E. coli*.

MATERIALS AND METHODS

Vegetal Material

To carry out this research, hydroponic watercress (*Nasturtium officinale* R. Br.) leaves from a local commercial company, located in Calera de Tango, Región Metropolitana, Chile, was used as raw material. The culture system was a floating root hydroponic system. The stocking density was three to five seeds per cell and seedlings (along with the substrate) were transplanted into hydroponic system when they reached an average of 8 cm in height, after approximately 25 days. The period from transplanting to harvest was 30 days and the collection was made manually and with sharp scissors at late afternoon.

Processing

Once the raw material was received from crop field, it was stored in a dark chamber at 5C and 90% relative humidity for 12 h. Damaged leaves and lignified or spoiled stems were removed or cut off using sharp disinfected knives. All the vegetal material was washed with tap cold water, followed by a second washing with sodium hypochlorite (50 mg/L, 5C, pH 6.5, 1 min; Clorox, Santiago, Chile). Leaves were rinsed out with sterile water to remove any residual of sodium hypochlorite on the leaves. Finally, leaves were drained on

a stainless steel mesh for 3 min and 1 min of hand centrifugation to remove the excess of water.

E. coli Inoculation

E. coli inoculum (ATCC 35218, Manassas, VA) preserved at 80C was suspended in a conical flask with 50 mL trypticase soy broth (Merck Chemicals, Darmstadt, Germany) with 0.6 g/mL yeast extract (Merck Chemicals). It was incubated at 37C for 24 h with constant stirring until a final concentration of 9 to 10 log cfu/mL.

The leaves were inoculated with *E. coli* nonpathogenic strain by spraying culture in aseptic conditions. An adaptation period of 24 h under dark and cold temperature (5C) conditions was allowed to settle down *E. coli* inoculums before treatment applications. The inoculation was performed reaching a concentration of about 8 to 9 log cfu per gram of leaves.

UV-C Treatments

Inoculated watercress leaves were subjected to six different doses of UV-C light (0 to 25 kJ/m^2). The application was made at a station chamber $1.28 \times 0.56 \times 0.60$ m (Model G-636, KBM Company, Santiago, Chile) equipped with type C ultraviolet lamps (TUV 36 W/G36 T8, Philips, Amsterdam, the Netherlands) arranged in two rows, with three lamps each one, at the top and the bottom of the chamber. The chamber had a central stainless steel mesh equidistant at the center (0.24 m) of the lamps, to support the samples, causing little interference with radiation coming from the bottom lamps set. The different UV-C doses were applied by modifying the exposure time. The emission rate of the lamps at the level of the samples was 0.344 kJ/s/m^2 and it was measured with a Radiometer VLX 254 (Vilber Lourmat, Torcy, France) at both sides of the steel mesh.

Packaging and Active Modified Atmosphere

After the application of different doses of UV-C light, 100 g of watercress were packed in polyethylene bags (San Jorge Packaging Company, Santiago, Chile), with dimensions of 0.25×0.2 m and permeability of 6.000 mL/m^2/day for O_2 and 19.000 mL/m^2/day for CO_2 at 23C and 1 atm.

To provide an active modified atmosphere, each bag was injected with a gas concentration of about 5 of O_2 and 10% CO_2, filling the rest of package with N_2 (85%). Thereafter, the bags were then sealed (Impulse Sealer Tew Equipment Co., Taipei, Taiwan). Five replicates of each treatment for each evaluation day were prepared and stored at 5C up to 12 days.

Gas evolution of O_2 and CO_2 inside the packages was determined by means of a portable gas analyzer (Checkpoint, GDP Dansensor, Rongsted, Denmark). All samples were analyzed to check that proper MAP conditions were achieved. Results were expressed as percentages of O_2 and CO_2.

Color

Leaf color was measured with a compact tri-stimulus colorimeter (Konica Minolta CR-300 Chroma Meter, Tokyo, Japan). The parameter values were registered as lightness ($L^\star$, where 0 = black, 100 = white), chroma ($C^\star = [a^{\star 2} + b^{\star 2}]^{1/2}$) and hue angle ($H_{ab} = 180 - tg^{-1} [b^\star/a^\star]$) (McGuire 1992). Color was measured on 10 leaves per package, on the adaxial side.

Survival of Nonpathogenic *E. coli* Strain

Samples of 10 g were homogenized in 90 mL of sterile 0.1% peptone buffered water (Merck Chemicals) in a sterile stomacher bag with a Colworth Stomacher 400 (model Easy Mix, AES Chemunex, Bruz, France) for 30 s. Serial dilutions for each replicate (three samples) were prepared in 0.1% peptone buffer as needed for plating three serial dilutions. Samples were taken on days 1, 4, 8 and 12 of storage. The survival and propagation analysis of the inoculated *E. coli* were experimentally conducted by platting serial dilutions in eosin methylene blue agar (Merck Chemicals), incubated at 37C for 2 days. Microbial counts were expressed as log cfu/g.

Sensory Analysis

Sensory analysis was applied under a descriptive quantitative analysis method with a panel of 12 judges, which recognize quality and features of fresh watercress, all of them defined as regular consumers. A linear scale was used to evaluate visual appearance and color intensity, where a judge panel adjudicated to watercress leaves different values from the best to the worst samples. Zero points were adjudicated to the worst product, with clear manifestation of decay and quality loss. Samples were randomized into white plates with three-digit code for identification.

Methanol-Soluble Phenolics

The watercress leaves were frozen at −80C until analysis. After that, about 1 g of frozen watercress was taken for the extraction of phenolic compounds and was homogenized

with methanol-water solution (50% v/v). The solution was homogenized for 2 min using an Ultra Turrax (IKA, T18 Basic, Königswinter, Germany) at 13,500 rpm. The mixture was centrifuged at 10,000 ×g in a thermoregulated centrifuge (Hermle Z 326K, Hermle Labortechnink, Wehngen, Germany) at 4C for 15 min. The supernatant was recovered and filtered through filter paper Whatman No. 2 (Sigma-Aldrich Chemicals, St. Louis, MI). Samples were analyzed according to Singleton and Rossi (1965), using the Folin–Ciocalteu reagent. The absorbance was measured at 660 nm with an UV-Vis spectrophotometer (T70 PG Instruments, Ltd., Leicester, U.K.). The results were expressed as µg of gallic acid equivalents per g fresh weight (µg GAE/g fw).

Antioxidant Capacity by FRAP

The antioxidant capacity of watercress leaves was based on the ability of the extracts to reduce Fe^{+3} to Fe^{+2} by ferric reducing ability of plasma (FRAP) method. This measurement was performed according to Benzie and Strain (1996) with some modifications.

For extract preparation, the sample was frozen with liquid nitrogen and crushed in a mortar to a fine powder. Then, 4.5 mL of ethanol : water (4:1) was added and filtered through filter paper Whatman No. 2 (Sigma-Aldrich Chemicals). Subsequently, the filtrate was centrifuged for 30 min at 10,000 ×g at 4C (326K Z, Hermle Labortechnink).

Watercress extracts (40 µL) were mixed with 900 µL of FRAP solution (300 mmol/L pH 3.5 of acetate buffer, ferric chloride hexo hydrous 20 mmol/L) and TPTZ [2, 4, 6-(tri-(2-pyridyl-s-triazine))] 10 mmol/L in 0.2 M HCl, and 60 µL of milli Q-water for reaction. Absorbance was measured at 593 nm until stable readings were reached. The results were expressed as µg Trolox equivalents per g of fresh weight (µg Trolox Equiv/g fw).

Statistical Analysis

Data were evaluated with analysis of variance. Significant differences between treatments were analyzed by comparing mean values by Tukey test ($P \leq 0.05$). MINITAB statistical software v.15 (Addlink Software Científico, S.L., Barcelona, Spain) was used for statistical analysis.

RESULTS AND DISCUSSION

Modified Atmosphere

Active modified atmosphere is usually applied in leafy vegetables to achieve the beneficial effects of moderate O_2 and CO_2 concentration corresponding to 5 of O_2 and 10% CO_2. Similar gas concentration has been previously suggested by
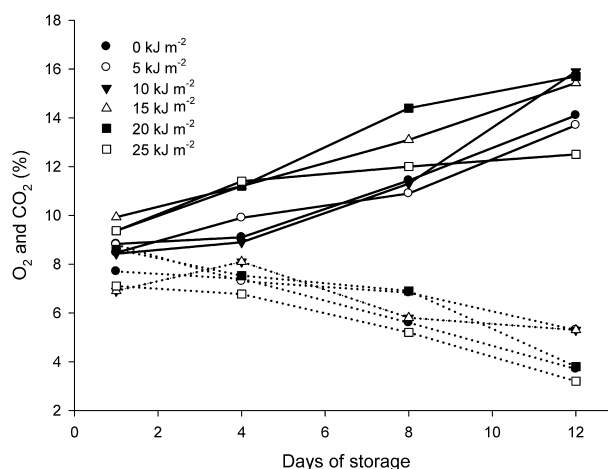

FIG. 1. GAS COMPOSITION (O_2 AND CO_2) OF MINIMALLY PROCESSED WATERCRESS TREATED BY UV-C LIGHT AND STORED UNDER MODIFIED ATMOSPHERE PACKAGING AT 5C DURING 12 DAYS

Dotted line correspond to percentage of O_2, full line correspond to percentage of CO_2. Vertical bars represent standard error of the means ($n = 5$).

Allende and Artés (2003) in Lollo Rosso lettuce and spinach cv. Emilia (Artés-Hernández *et al.* 2009). Throughout the storage period, the concentration of CO_2 increased from 8–10% to values between 11.5 and 15.9%, with no significant differences among treatments (Fig. 1). The tendency of O_2 concentration was to decrease, from 7–9% to the final values of 3.2–5.3%, without significant difference among treatments. Results were explained by the product respiration and the gas diffusion rate across the film (Allende and Artés 2003). The UV-C light doses did not affect gas concentration within package during cold storage. Nevertheless, several reports have shown that higher UV-C doses activate multiple biological processes in vegetables, including stimulation of respiratory activity causing a higher CO_2 production (Allende *et al.* 2006). The proper selection of the packaging material allowed reaching desired final atmosphere composition for conservation of watercress under cold storage.

Color

Lightness (*L**). After 8 days at 5C, watercress leaves treated with 10 kJ/m² had a lower lightness value ($L^* = 37.8$) compared with the other treatments ($L^* = 45$ to 50). At the end of storage (day 12), there were no significant differences among treatments. Generally, a high value of L^* could be associated with a light green color. Overall, this shows that lightness was unaffected by the UV-C treatments (Fig. 2A).

Chroma (*C**). After 8 days at 5C, untreated UV-C watercress leaves had a higher chroma values than other
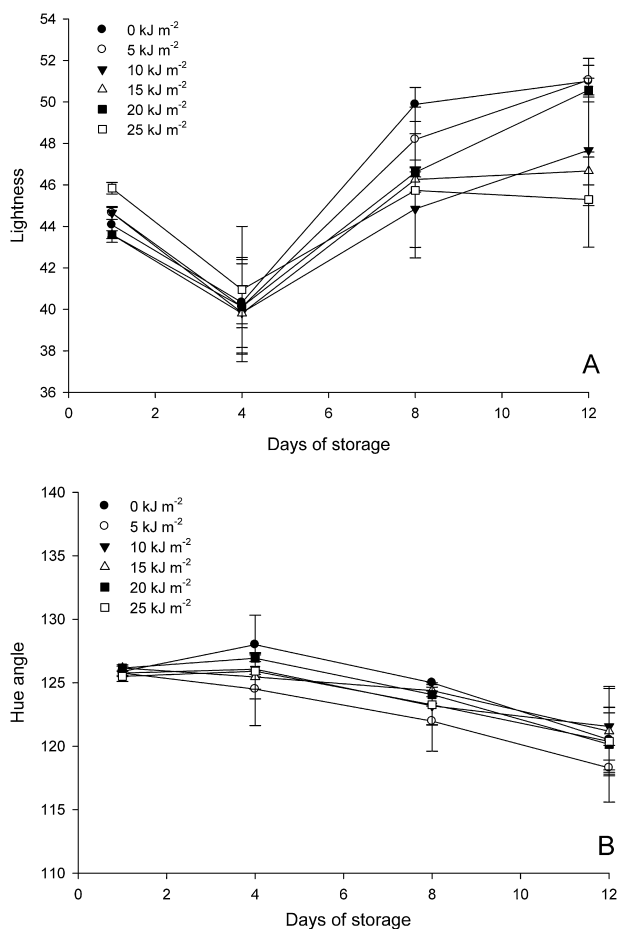
FIG. 2. COLOR PARAMETERS
(A) Lightness; (B) hue angle of minimally processed watercress treated by UV-C light and stored under modified atmosphere packaging at 5C during 12 days. Vertical bars represent standard error of the means ($n = 50$).

treatments, which showed values between 27 and 31. A high value of chroma must be related to color intensity that would indicate that the UV-C light delayed the color changes. In this investigation, there were no significant differences ($p \leq 0.05$) among the applied treatments at the end of storage (day 12; data not shown). Artés-Hernández *et al.* (2009) did not find initially significant differences between UV-C-treated shredded spinach and control samples stored for 13 days at 5C.

H_{ab}. In all treatments, hue angle values showed no significant differences among treatments at all sampling dates. However, a decreasing trend was observed in hue values throughout cold storage (Fig 2B). The reduction in this parameter corresponded to the loss of green color and increased yellowing that could be related to senescence of leaves (Gonçalves *et al.* 2009). Some authors have shown an

inhibitory effect of UV-C light on chlorophyll breakdown by modifying activity rates of enzymes involved in this process as chlorophyllase, chlorophyll degrading peroxidase and Mg-dechelatase, keeping chlorophyll for long periods of storage (Funamoto *et al.* 2002; Costa *et al.* 2006; Mahdavian *et al.* 2008; Chairat *et al.* 2013). Also, the modified atmosphere condition with low O_2 and moderate CO_2 levels reached during this study would help to decrease the color changes of the leaves (Artés *et al.* 2009). Color is one of the most important characteristics of watercress leaves, and it is the major problem in postharvest because of rapid senescence, which is reflected in the yellowing of the leaves, resulting from the degradation of chlorophyll (Hinojosa *et al.* 2013).

Nonpathogenic *E. coli* Strain Survival

The day after processing, the untreated inoculated leaves of watercress presented an initial count of 8.6 log cfu/g, which was significantly higher than the treated UV-C samples (6.9 to 7.2 log cfu/g; Fig. 3). A slight reduction in all UV-C treatments compared with control was found on day 4. This would indicate an effect of UV-C light reducing survival and proliferation of inoculated *E. coli*. On day 8, the doses of 20 and 25 kJ/m^2 had significant reduction in counts (reaching 3.3 log cfu/g reductions) compared with other treatments. The same trend was followed after 12 days showing that UV-C doses had a significant delay in microbial growth. These reductions were higher than previously reported by Yaun *et al.* (2004) that applied UV-C doses
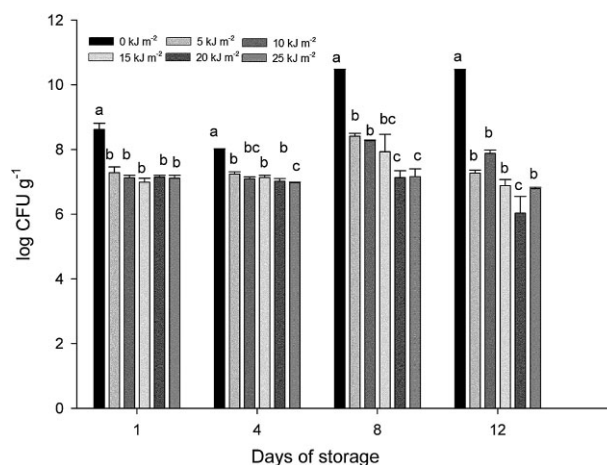

FIG. 3. *Escherichia coli* SURVIVAL (LOG10 CFU/G) OF MINIMALLY PROCESSED WATERCRESS TREATED BY UV-C LIGHT AND STORED UNDER MODIFIED ATMOSPHERE PACKAGING AT 5C DURING 12 DAYS
Vertical bars represent standard error of the means ($n = 5$). Small letters: values followed by the same small letter are not significantly different ($p \leq 0.05$).

from 9 to 24 kJ/m^2 on lettuce leaves reaching log reductions of *Salmonella* spp. and *E. coli* O157:H7 (2.65 and 2.79, respectively). The effectiveness of UV-C light depends on the structure and topography of the surface area where it is applied. Bacterial sensitiveness to UV-C varies within species and also among the different strains of the same species (Guerrero-Beltrán and Barbosa-Cánovas 2004; Escalona *et al.* 2010).

Sensory Quality

Visual Appearance. The UV-C light did not affect visual appearance of leaves during 12 days of storage compared with control (Fig. 4A). Similar results have been found with doses of 6 and 18 kJ/m^2 on MP watercress packaged on

FIG. 4. SENSORY QUALITY OF MINIMALLY PROCESSED WATERCRESS TREATED BY UV-C LIGHT AND STORED UNDER MODIFIED ATMOSPHERE PACKAGING AT 5C DURING 12 DAYS
(A) Visual appearance; (B) color intensity. Vertical bars indicate the standard error of the means (*n* = 12). Small letters: values followed by the same small letter are not significantly different (*p* ≤ 0.05).

passive modified atmosphere and storage for 7 days at 5C and 90% relative humidity. According to Hinojosa *et al.* (2013), 18 kJ/m^2 had a slight effect on visual appearance, getting lower scores than the samples treated with 6 kJ/m^2 after 14 days at 5C. Artés-Hernández *et al.* (2009) did not find visual appearance differences between UV-C-treated shredded spinach and control during 13 days at 5C. Even though significant differences were not detected among UV-C light and control (*p* ≤ 0.05), the decreased scores during the storage could be more related to the slight water condensation and the colonization of microorganisms on the surface of leaves.

Color Intensity. The longest color preservation was observed on leaves treated with lowest UV-C doses, similar to control (Fig. 4B). Apparently, doses higher than 15 kJ/m^2 could favor the green color losses after 4 days although this was not observed by instrumental measurements (Fig. 2). High UV-C doses could increase free radical production and senescence of plant tissues as was reported by Allende and Artés (2003). These authors found in chopped lettuce that 7.1 kJ/m^2 after 10 days at 5C caused browning and texture damages. It was described that a progressive solubilization of the pectin layers in the vegetal cell wall could be stimulated by UV-C (Pombo *et al.* 2009). The visual appearance on food is a primary consideration that consumers take into account. Color has a key role in the choice of food and acceptability (Rico *et al.* 2007). If an MP vegetable shows an unacceptable visual quality, a potential consumer will not experience the other attributes such as taste, texture and smell, and will not be interested to buy or consume the product (Martínez-Sánchez *et al.* 2008).
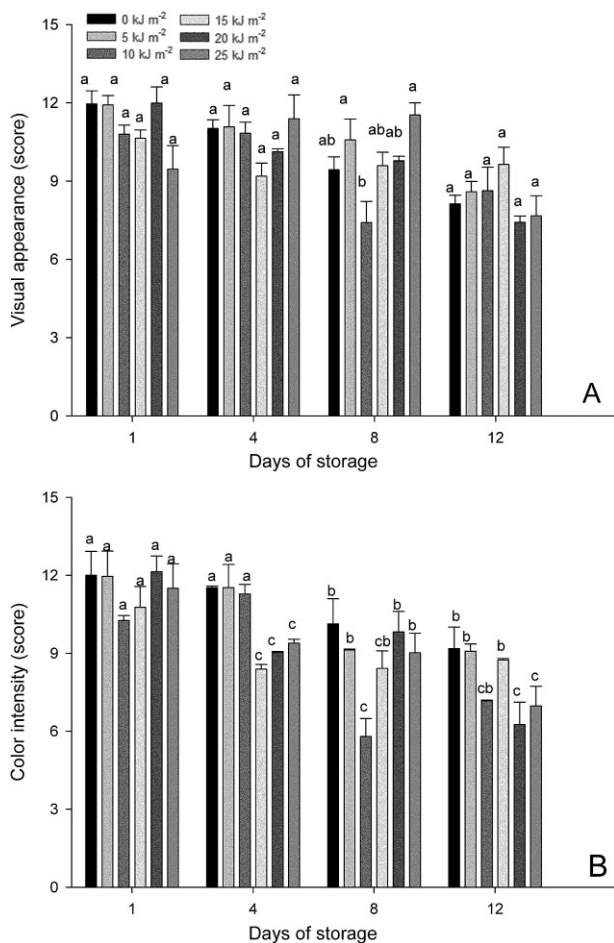
Methanol-Soluble Phenolics

On day 1, there were no significant differences among treatments with average values of 2.7 μg GAE/g fw. On days 4 and 8, all treatments reached similar values between 1.6 and 2.5 μg GAE/g fw. On day 12, treatments between 15 and 25 kJ/m^2 had significantly higher mean values of 2.4 μg GAE/g fw than other doses (Fig. 5). Methanol-soluble phenolic compounds are substances involved in maintaining the antioxidant capacity of the tissues. UV-C light has a significant effect to increase the methanol-soluble phenolic content; it could stimulate the production of phenylalanine ammonia-lyase and the formation of phytoalexins (phenolic compounds; Cuvi *et al.* 2011). The results obtained in this study showed that control treatment had reduced methanol-soluble phenolic content along storage period similar to treatment of 5 kJ/m^2. After day 4, methanol-soluble phenolic content increased from 1.5 to 3.0 μg GAE/g fw for those treated with UV-C doses higher than 5 kJ/m^2, particularly those with 20 kJ/m^2 that presented a
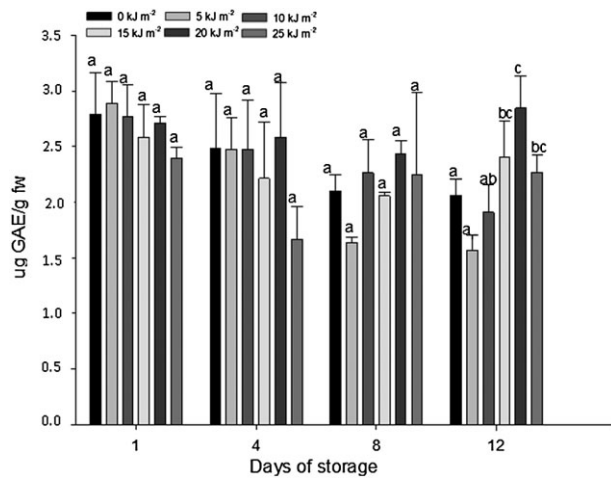
FIG. 5. METHANOL-SOLUBLE PHENOLIC CONTENT (ug GAE/g fw) OF MINIMALLY PROCESSED WATERCRESS TREATED BY UV-C LIGHT AND STORED UNDER MODIFIED ATMOSPHERE PACKAGING AT 5C DURING 12 DAYS
Vertical bars represent standard error of the means (*n* = 5). Small letters: values followed by the same small letter are not significantly different (*p* ≤ 0.05).

FIG. 6. ANTIOXIDANT CAPACITY (ug Trolox Equiv/g fw) OF MINIMALLY PROCESSED WATERCRESS TREATED BY UV-C LIGHT AND STORED UNDER MODIFIED ATMOSPHERE PACKAGING AT 5C DURING 12 DAYS
Vertical bars represent standard error of the means (*n* = 5).

final content of 2.8 μg GAE/g fw at day 12 of storage. Studies of Ruiz *et al.* (2010) found in cabbage leaves treated with UV-C light a significant increase in polyphenol content than the control after 2 and 9 days at 6C.

It must be considered that high doses of UV-C light could exert visible damage to the surface of vegetables and the extent of this phenomenon depends on the stage of maturity and cultivar treated (Allende and Artés 2003). As mentioned earlier, visual appearance and color intensity could be affected by UV-C when the doses exceed 10 kJ/m². Based on this result, it could be suggested that UV-C doses ≤ 15 kJ/m² could preserve the sensorial quality but does not necessarily help to improve the functional quality of vegetables along cold storage.

Antioxidant Capacity by FRAP

Throughout the cold storage, no significant differences among treatments were found. All treatments along the assay period showed antioxidant capacity in the range of 0.12 to 0.2 μg Trolox equivalents/g fw (Fig. 6). In general, samples (with and without UV-C light exposition) showed a steady decline until day 4. This response could be due to the processing operations which cause oxidative stress in cell membrane. Artés-Hernández *et al.* (2009) did not find significant differences in antioxidant capacity on spinach leaves treated or untreated with UV-C packed in modified atmosphere and stored at 5C. In the same study, the general trend was to decrease over time, and after 13 days,
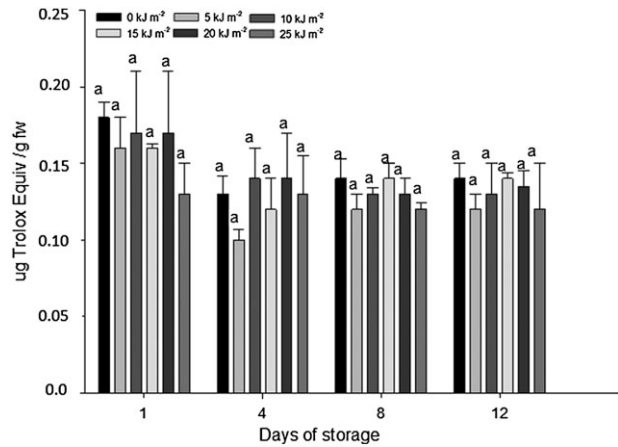
the treated samples showed values significantly lower than the control. However, Ruiz *et al.* (2010) determined that the UV-C-treated cabbage leaves had a significantly higher antioxidant capacity than the control after 2 and 9 days at 6C.

CONCLUSIONS

Results suggest that the proposed UV-C doses and modified atmosphere may be useful as innovative techniques to the MP industry maintaining a fresh visual appearance of MP watercress. High UV-C doses reduced and had a bacteriostatic effect on *E. coli* loads reaching reductions of 3.3 log on microbial counts, allowing the commercialization of watercress until 12 days at 5C.

In addition, promising results were observed for phenolic content of vegetables exposed to high UV-C doses (15 to 25 kJ/m²). However, along with an increase in phenolics, a slight decrease in the sensory quality of watercress was noticed. Our results confirm that UV-C could be a valuable tool for the MP industry in order to guarantee the safety of food products.

ACKNOWLEDGMENTS

REFERENCES

ALLENDE, A. and ARTÉS, F. 2003. UV-C radiation as a novel technique for keeping quality of fresh processed *Lollo Rosso* lettuce. Food Res. Int. *36*, 739–746.

ALLENDE, A., MCEVOY, J., ARTÉS, F. and WANG, C. 2006. Effectiveness of two-sided UV-C treatments in inhibiting natural microflora and extending the shelf-life of minimally processed "Red Oak Leaf" lettuce. Food Microbiol. *23*, 241–249.

ARTÉS, F., CONESA, A., LÓPEZ-RUBIRA, V. and ARTÉS-HERNÁNDEZ, F. 2006. UV-C treatments for improving microbial quality in whole and minimally processed bell peppers. In *The Use of UV as a Postharvest Treatment: Status and Prospects* (S. Ben-Yehoshua, G.D. Hallewin, G. Erkan, M. Rodov and V. Lagunas, eds.) pp. 12–17, Ofset-akup Kublay, Antalya.

ARTÉS, F., GÓMEZ, P., AGUAYO, E., ESCALONA, V. and ARTÉS-HERNÁNDEZ, F. 2009. Sustainable sanitation techniques for keeping quality and safety of fresh-cut commodities. Postharvest Biol. Technol. *51*, 287–296.

ARTÉS-HERNÁNDEZ, F., ESCALONA, V.H., ROBLES, P.A., MARTÍNEZ-HERNÁNDEZ, G.B. and ARTÉS, F. 2009. Effect of UV-C radiation on quality of minimally processed spinach leaves. J. Sci. Food Agric. *89*, 414–421.

BAKA, M., MERCIER, J., CORCUFF, F., CASTAIGNE, F. and ARUL, J. 1999. Photochemical treatment to improve storability of fresh strawberries. J. Food Sci. *68*, 1068–1072.

BENZIE, I.F.F. and STRAIN, J.J. 1996. The ferric reducing ability of plasma (FRAP) as a measure of "antioxidant power": The FRAP assay. Anal. Biochem. *239*, 70–76.

BINTSIS, T., LITOPOULOU-TZANETAKI, E. and ROBINSON, R. 2000. Existing and potential applications of ultraviolet light in the food industry – a critical review. J. Sci. Food Agric. *80*, 637–645.

CHAIRAT, B., NUTTHACHAI, P. and VARIT, S. 2013. Effect of UV-C treatment on chlorophyll degradation, antioxidant enzyme activities and senescence in Chinese kale (*Brassica oleracea* var: *alboglabra*). Int. Food Res. J. *20*, 623–628.

COSTA, L., VICENTE, A., CIVELLO, P., CHAVES, A. and MARTÍNEZ, G. 2006. UV-C treatment delays postharvest senescence in broccoli florets. Postharvest Biol. Technol. *39*, 204–210.

CUVI, M.J., VICENTE, A., CONCELLÓN, A. and CHAVES, A. 2011. Changes in red pepper antioxidants as affected by UV-C treatments and storage at chilling temperatures. LWT – Food Sci. Technol. *44*, 1666–1671.

ERKAN, M., WANG, C. and KRIZEK, D. 2001. UV-C radiation reduces microbial populations and deterioration in *Cucurbita pepo* fruit tissue. Environ. Exp. Bot. *45*, 1–9.

ESCALONA, V.H., AGUAYO, E., MARTÍNEZ-HERNÁNDEZ, G. and ARTÉS, F. 2010. UV-C doses to reduce pathogen and spoilage bacterial growth *in vitro* and in baby spinach. Postharvest Biol. Technol. *56*, 223–231.

FUNAMOTO, Y., YAMAUCHI, N., SHIGENAGA, T. and SHIGYO, M. 2002. Effects of heat treatment on chlorophyll degrading enzymes in stored broccoli (*Brassica oleracea* L.). Postharvest Biol. Technol. *24*, 163–170.

GAYÁN, E., MONFORT, S., ÁLVAREZ, I. and CONDÓNET, S. 2011. UV-C inactivation of *Escherichia coli* at different temperatures. Innov. Food Sci. Emerg. *12*, 531–541.

GIL, M.I., AGUAYO, E. and KADER, A. 2006. Quality changes and nutrient retention in fresh-cut versus whole fruits during storage. J. Agric. Food Chem. *54*, 4284–4296.

GIL, M.I., SELMA, M.V., LÓPEZ-GÁLVEZ, F. and ALLENDE, A. 2009. Fresh-cut product sanitation and wash water disinfection: Problems and solutions. Int. J. Food Microbiol. *134*, 37–45.

GONÇALVES, E.M., CRUZ, R.M.S., ABREU, M., BRANDAO, T.R.S. and SILVA, C.L.M. 2009. Biochemical and color changes of watercress (*Nasturtium officinale* R.Br.) during freezing and frozen storage. J. Food Eng. *93*, 32–39.

GUAN, W., FAN, X. and YAN, R. 2012. Effects of UV-C treatment on inactivation of *Escherichia coli* O157:H7, microbial loads, and quality of button mushrooms. Postharvest Biol. Technol. *64*, 119–125.

GUERRERO-BELTRÁN, J.A. and BARBOSA-CÁNOVAS, G.V. 2004. Advantages and limitations on processing foods by UV light. Food Sci. Technol. Int. *10*, 137–147.

HARRIS, L.J., FARBER, J.N., BEUCHAT, L.R., PARISH, M.E., SUSLOW, T.V., GARRET, E.H. and BUSTA, F.F. 2003. Outbreaks associated with fresh produce: Incidence, growth, and survival of pathogens in fresh and fresh-cut produce. Compr. Rev. Food Sci. Food Saf. *2*, 78–142.

HINOJOSA, A., SILVEIRA, A.C., OSPINA, M., CHAR, C., SÁENZ, C. and ESCALONA, V.H. 2013. Safety of ready-to-eat watercress using environmentally friendly sanitization methods. J. Food Qual. *36*, 66–76.

MAHDAVIAN, K., GHORBANLI, M. and KALANTARI, K.H.M. 2008. The effects of ultraviolet radiation on the contents of chlorophyll, flavonoid, anthocyanin and proline in *Capsicum annuum* L. Turk. J. Bot. *32*, 25–33.

MARTÍNEZ-SÁNCHEZ, A., ALLENDE, A., CORTES-GALERA, Y. and GIL, M.I. 2008. Respiration rate response of four baby leaf *Brassica* species to cutting at harvest and fresh-cut washing. Postharvest Biol. Technol. *47*, 382–388.

MCGUIRE, R. 1992. Reporting of objective color measurements. Hortscience *27*, 1254–1255.

OMS-OLIU, G., ROJAS-GRAÜ, M.A., ALANDES, L., VARELA, P., SOLIVA-FORTUNY, R., HERNANDO, M.I., PÉREZ, I., FISZMAN, S. and MARTÍN-BELLOSO, O. 2010. Recent approaches using chemical treatments to preserve quality of fresh-cut: A review. Postharvest Biol. Technol. *57*, 139–148.

POMBO, M.A., DOTTO, M.C., MARTÍNEZ, G.A. and CIVELLO, P. 2009. UV-C irradiation delays strawberry fruit softening and modifies the expression of genes involved in cell wall degradation. Postharvest Biol. Technol. *51*, 141–148.

RICO, D., MARTÍN-DIANA, A.B., BARAT, J.M. and BARRY-RYAN, C. 2007. Extending and measuring the quality of fresh-cut fruit and vegetables: A review. Trends Food Sci. Technol. *18*, 373–386.

ROJAS-GRAÜ, M.A., OMS-OLIU, G., SOLIVA-FORTUNY, R. and MARTÍN-BELLOSO, O. 2009. The use of packaging techniques to maintain freshness in fresh-cut fruits and vegetables: A review. Int. J. Food Sci. Technol. *44*, 875–889.

RUIZ, G.A., QÜESTA, A.G. and RODRÍGUEZ, S.C. 2010. Efecto de luz UV-C sobre las propiedades antioxidantes y calidad sensorial de repollo mínimamente procesado. Rev. Iberoam. Tecnología Postcosecha *11*, 101–108.

SINGLETON, V.I. and ROSSI, J.A. 1965. Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. Am. J. Enol. Vitic. *16*, 144–158.

SLAVIN, J. and LLOYD, B. 2012. Health benefits of fruits and vegetables. Adv. Nutr. *3*, 506–516.

YAUN, B.R., SUMNER, S.S., EIFERT, J.D. and MARCY, J.E. 2004. Inhibition of pathogens on fresh produce by ultraviolet energy. Int. J. Food Microbiol. *90*, 1–8.