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REVIEW ARTICLE

Prospects of UV radiation for application in postharvest technology

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Abstract

UV light has been used as a germicidal agent in water treatment and surfaces disinfection because of its capacity to affect DNA of microorganisms. On the other hand, low doses of UV-C irradiation can trigger some favourable reactions in biological organs, such as fruits and vegetables, which can lead to various beneficial effects, such as improvement of their shelf-life or increase in the content of health promoting components. The objective of this work is to review the results of some recent works on the UV application on post harvested fruits and vegetables taking into account both, its direct germicidal activity and its hormectic effects. After the presentation of the hormesis concept, the application of UV to read-to-use fruit and vegetables and, specifically, to various fruits and vegetables, is discussed. The use of UV radiation strictly for hormectic purposes at commercial scale, still needs to be further investigated.

Key words: UV light, UV-B, UV-C, Postharvest technology, Fruits, Vegetables, Hormesis

Introduction

Although the use of ultra-violet light (UV) is well established for water treatment, air disinfection, and surface decontamination, its use is still limited in food treatment and in postharvest technology in particular. UV treatment has a potential for commercial use as a surface treatment of fresh-cut fruits. The ability of UV light to sanitize and retard microbial growth on the surface of fresh-cut fruits without causing undesirable quality changes has recently been recognized. Irradiation with UV light may be a more effective germicidal treatment than chlorine, hydrogen peroxide, or ozone. Recent advances in the science and engineering of UV-light irradiation have demonstrated that UV treatment holds considerable promise for shelf-life extension of fresh fruits and vegetables. Considering its importance, surprisingly little is known about the interaction of UV light with matter, especially with a complex food matrix.

The objective of this review is by no means to describe exhaustively and in detail all the work done on the effects of UV radiation on vegetables and fruits, but only to report some of the recent results that can lead to the use of UV light to postharvest treatment of fruits and vegetables.

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UV light

Light is just one portion of the electromagnetic spectrum which covers a broad range from radio waves with wavelength of a meter or more, down to x-rays with wavelength of less than a billionth of a meter. Typically, the wavelength for UV processing ranges from 100 to 400 nm (Koutchma et al., 2009). This range may be further subdivided into UV-A (315–400 nm), normally responsible for changes in human skin called tanning; UV-B (280–315 nm), which can cause skin burning and eventually lead to skin cancer; UV-C (200–280 nm), called the germicidal range, since it effectively inactivates bacteria and viruses; and the vacuum UV range (100–200 nm), which can be absorbed by almost all substances and thus can be transmitted only in a vacuum (Koutchma et al., 2009) . Short UV-C is almost completely absorbed in air within a few hundred meters. When UV-C photons collide with oxygen atoms, the energy exchange causes the formation of ozone. UV-C is almost never observed in nature, since it is absorbed so quickly.

Koutchma et al. (2009) reviewed the full range of commercially available UV sources, such as low- and medium-pressure mercury lamps, mercury-free amalgam lamps, and discussed the advantages of the pulsed UV-light sources currently under development.

The concept of hormesis

UV-C irradiation at low doses (0.25–8.0 kJ/m^2) affects the DNA of microorganisms (Terry and Joyce, 2004). For this reason UV-C treatment has

been used as a germicidal or mutagenic agent. In addition to this direct germicidal activity, UV-C irradiation can modulate induced defence in plants. So UV-C irradiation can be applied at lethal and sublethal doses. UV-C can also produce a detrimental effect on plant tissues which includes tissue structural damage, changes in cytomorphology and water permeability of inner epidermal cells (Lichtscheidl-Schultz, 1985). Nevertheless, low doses of UV-C irradiation stimulated beneficial reactions in biological organs, a phenomenon known as hormesis (Shama, 2007). Hormesis is defined as the stimulation by low doses of any potentially harmful agent (Luckey, 1980). The agents capable of bringing about these stimulatory effects may be either chemical or physical ones. Included amongst the latter are various portions of the electromagnetic spectrum. Luckey (1980) conducted an extensive survey of hormetic effects induced by both ionizing radiation and UV light.

Hormesis involves stimulation of a beneficial plant response by low or sub-lethal doses of an elicitor/agent, such as a chemical inducer or a physical stress (Terry and Joyce, 2004). Non-ionising radiation has real potential amongst physical methods for controlling postharvest diseases (Wilson et al., 1997).

According to Shama (2007), hormesis involves the use of small doses of potentially harmful agents directed against a living organism or living tissue in order to elicit a beneficial or protective response. Hormetic UV treatment is distinguished from conventional UV treatment. In conventional treatment the UV is directed at microorganisms present on the surfaces of an object, whereas in hormetic UV treatment the object itself is the target of the incident UV. The objective of the treatment is to elicit an antimicrobial response in the fruit and vegetable tissue. Both types of UV treatment employ the same wavelengths, but for hormetic treatments only low UV doses are required.

Low doses of short-wave ultra-violet light (UV-C, 190–280 nm wavelengths) can control many storage rots of fruit and vegetables. It has been reported that hormetic doses of UV-C can prolong the postharvest life and maintain the quality of fruits. These effects include delay of senescence process and fruit ripening (Gonzalez-Aguilar et al., 2007a), induction of natural defence and elicitors against fungi and bacteria (Alothman et al., 2009a).

Exposure to hermetic doses of UV radiation triggers a series of biochemical events within the plant tissue, and a number of quite distinct responses have been identified. Some responses involve the synthesis of enzymes that have activity against molds, while others result in the generation of a host of so-called phytoalexins, which are inhibitory to microorganisms. These effects are produced by the use of very low UV doses, and the time scale for the induction of such events is measured over hours or even days. Resistance to infection by pathogen is correlated with the induction of plant defence mechanism (Gonzalez- Aguilar et al. 2007b) and DNA damage (Charles et al., 2009). This is manifested through the stimulation of anti- fungal chemical species such as phytoalexins (scoparone and resveratrol), flavonoids, and degrading fungal cell-wall enzymes (chitinases, glucanases) (El-Ghaouth et al., 1998). The induction of plant defence system can also trigger the accumulation of these compounds and other phytochemicals such as carotenoids and vitamin C which exhibit antioxidant potential, improving the nutritional status of the fruit (Alothman et al., 2009a, 2009b; Gonzalez- Aguilar et al., 2007a, 2007b).

All published work on the delivery of low doses of UV to fresh produce has concerned itself with only relatively small numbers of fruit treated under laboratory conditions, and little consideration has been given to how produce may be treated on a large scale under industrial conditions. Shama (2007) considered the prospects of treating fruits with UV on a commercial scale. According to this author, any process for irradiating produce must fulfil certain essential requirements (Shama, 2007) such as: produce should not be subjected to any form of mechanical handling during irradiation that might cause it to become damaged; there should be provision for both varying the UV dose delivered and controlling the dose; UV-C treatment should not add unduly to processing costs; the design of equipment should enable high throughputs to be treated; ideally, a wide variety of different types of fruit and vegetables should be treatable.

Postharvest UV radiation: effects and possible technological applications

Ready-to-use fruit and fresh vegetables

The market sales of ready-to-use fruit and fresh vegetables have grown rapidly in recent years due to the health benefits associated with these foods. Its growth has heightened awareness about the microbiological and physiological parameters associated with quality in fresh ready-to-eat vegetables due to the relevance for industry and its economic impact. Chlorine solutions have been widely used to sanitise fruit and vegetables in the

fresh-cut industry and continues being the most commonly used sanitizer due to its efficacy, cost-effectiveness ratio and ease to use. However, chlorine has been associated with the possible formation of carcinogenic chlorinated compounds (Rico et al., 2007). This preoccupation urges fresh-cut industry to find new alternatives. These alternatives must satisfy the consumers and maintain a balance between sensory and quality. For this reason exploration and enhancement of new alternatives are essential. There is a real need to find alternatives for preservation of fresh-cut fruit and vegetables in order to improve the efficacy of washing treatments. Alternatives or modified methods have been proposed, as antioxidants, irradiation, ozone, organics acids, modified atmosphere packaging, whey permeate, etc.; however, none have yet gained widespread acceptance by the industry (Rico et al., 2007).

New techniques for maintaining quality and inhibiting undesired microbial growth are demanded in all the steps of the production and distribution chain. Allende et al. (2006) summarized and discussed some of the new techniques available in the fresh-cut industry such as the combination of sanitizers with other methods, combinations of physical and chemical treatments, the use of ultraviolet-C radiation, modified-atmospheres, heat shocks and ozone treatments, alone or in different combinations, in order to control microbial growth and maintain quality during storage of fresh-cut produce.

It has been reported that UV–C affects several physiological processes in plant tissues and, what it is more important, damages microbial DNA (Kuo et al., 1997; Lucht et al., 1998). Lado and Yousef (2002) reported that UV–C radiation from 0.5 to 20 kJ/m^2 inhibited microbial growth by inducing the formation of pyrimidine dimers which alter the DNA helix and block microbial cell replication. Therefore, cells which are unable to repair radiation-damaged DNA die and sub-lethally injured cells are often subject to mutations. A number of *in vitro* studies have demonstrated the efficiency of UV–C radiation on microbial inhibition (Gardner and Shama, 2000). Abshire and Dunton (1981) found that some species (*Pseudomonas aeruginosa*) were more sensitive than others (*Micrococcus radiodurans* and *Candida albicans*). Consistent with this, Sumner et al. (1995) found that UV–C was effective in destroying *Salmonella typhimurium* on agar plates.

Selma et al. (2008) investigated the disinfecting efficacy of ozone (O_3) and UV-C illumination, and their combination for reduction microbial flora of fresh-cut onion, escarole, carrot, and spinach wash waters collected from the industry. They achieved a maximum microbial reduction of 6,6 log CFU mL^{-1} after 60 min treatment with O_3-UV and concluded that O_3 and O_3–UV are alternatives to other sanitizers used in the fresh-cut washing processes. The use of these technologies would allow less frequent changing of spent water and the use of much lower sanitizer doses. Nevertheless, in specific applications where levels of undesirable microbial and chemical constituents are lower, UV treatment alone could be an appropriate treatment considering cost-effectiveness criteria.

Postharvest treatments of either ClO_2 or fumaric acid combined with UV-C can be useful for maintaining the quality of strawberries, including the sensory evaluations scores (Kim et al., 2010). These authors examined the combined effect of aqueous chlorine dioxide (ClO_2) or fumaric acid with ultraviolet-C (UV-C) on postharvest quality of 'Maehyang' strawberries. The strawberries were treated with distilled water, 50 mg L^{-1} ClO_2 , 0.5% fumaric acid, 5 kJ/m^2 UV-C irradiation, and a combination of 50 mg L^{-1} ClO_2/5 kJ/m^2 UV-C and 0.5% fumaric acid/5 kJ/m^2 UV-C. The combined treatment of fumaric acid/UV-C reduced the initial populations of total aerobic bacteria and yeast and molds in the strawberries by 2.25 and 2.01 log CFU g^{-1}, respectively. Sensory evaluation results indicated that the combined treatment provided better sensory scores than did the control.

Tomatoes

The use of UV-light could be employed to improve tomato nutritional qualities and lycopene content without inducing significant changes to the physical properties of tomatoes during post-harvest storage. Liu et al. (2009) treated harvested mature-green (breaker-stage) tomatoes with short bursts of UV-C, red light or sun light for up 21 days. The concentration of lycopene in tomato exocarp was significantly increased after 4 days and dramatically enhanced by UV-C or red light treatments. However, the concentration of β-carotene was not affected by UV-C or red light treatments, and decreased by sun light treatment during 21 days of storage, compared to the control samples. The colour (a* and b* values) and force required to penetrate the tomatoes were, to a small but significant extent, influenced by the light treatments. The total soluble refractive solids of all tomato samples remained the same throughout storage.

Liu et al. (2011a) studied gene expression of tomato fruit in response to postharvest UV-C irradiation (4 kJ/m^2), during 24 h after the treatment. They concluded that UV-C irradiation can induce the expression of a number of defence response genes, and suppress the expression of major genes involved in cell wall disassembly, lipid metabolism and photosynthesis. These gene changes underline the biochemical and physiological changes induced by UV-C such as increased defence ability, delayed softening, better maintenance of nutritional and sensory qualities and extension of shelf-life in tomato fruit.

UV-treatments of tomato fruits reduce the gloss of the tomato surface because those treatments affect the morphology of fruit surface wax (Charles et al., 2008a). UV-treatment may have induced biochemical modifications of the surface wax layers. The overall impact of these changes has two contrasting effects. On the one hand, changes in the physical and biochemical modifications that occur in the epidermal cell in response to UV-treatment may be conducive to an improved ability of the plant tissue to resist pathogen attack. On the other hand, altered wax layers can affect light reflectance characteristics of the fruit surface, and may also contribute to increased water loss from cuticular transpiration, both leading to changes in the appearance of the fruit.

Charles et al. (2008b) treated postharvest tomato fruit with the dose of 3.7 kJ/m2 of UV-C, which had shown optimal for inducing decay resistance, but whose treatment caused ultrastructural modifications in the pericarp. UV induced plasmolysis of the epicarp cells as well as some cell layers of the mesocarp. Collapse of these cells led to the formation of a cell wall stacking zone which restricted *Botrytis cinerea* development to the outer most part of the fruit and hindered its progression toward the inner tissues.

Charles et al. (2008c) studied the biochemical nature of cell wall modifications induced by UV-C in postharvest tomato fruit and they found that UV treatment induced the accumulation of phenolic compounds and the formation of lignin and suberin. Simple phenolic compounds induced by UV-C appear to have a fungistatic effect; and complex phenolics, lignin and suberin, play a barrier role physically impeding pathogen ingress by strengthening the cell wall stacking zone. Such a barrier would also reduce diffusion of nutrients and water from the plant tissue required to sustain fungal growth, and toxins and cell wall degrading enzymes from the fungus, which interfere with virulence of the pathogen.

UV-B irradiation appears to be a useful non-chemical way of maintaining postharvest quality and enhancing antioxidant capacity in tomato fruit. Liu et al. (2011b) applied doses between 20 and 80 kJ/m^2 to mature-green tomato of UV-B irradiation. 20 or 40 kJ/m^2 was most effective in maintaining a high level of firmness and delaying the colour development. Furthermore, 20 or 40 kJ/m^2 promoted the accumulation of total phenolic and total flavonoids, and enhanced antioxidant capacity during storage, though UV-B irradiation could reduce the ascorbic acid content. A dose of 10 kJ/m^2 had similar effects but to a lesser extent. The highest dose of 80 kJ/m^2 resulted in higher lycopene content, but showed negative effects on texture, colour, and other antioxidants. The optimum dose of UV-B for maintaining sensory qualities and enhancing antioxidant capacity was 20 or 40 kJ/m^2.

Mushrooms

UV-C radiation could potentially be used for sanitizing fresh mushrooms and may be a useful non-chemical way of maintaining mushroom quality and extending their postharvest life.

Guan et al. (2012) investigated the effects of UV-C light, applied to both sides of mushrooms, on microbial loads and product quality, during 21 days of storage at 4 ◦ C. Microflora populations, color, antioxidant activity, total phenolics, and ascorbic acid were measured at 1, 7, 14 and 21 days of storage. Additionally, the inactivation of *Escherichia coli* O157:H7 by UV-C was determined. Results showed that UV-C doses of 0.45–3.15 kJ/m^2 resulted in 0.67–1.13 log CFU g^{-1} reduction of *E. coli* O157:H7 inoculated on mushroom cap surfaces. UV-C radiation also reduced total aerobic plate counts by 0.63–0.89 log CFU g^{-1} on the surface of mushrooms. In addition, the UV-C treatments apparently inhibited lesion development on the mushroom surface. During the first 7 days, irradiated mushrooms had lower antioxidant activity, total phenolics, and ascorbic acid content than non-radiated samples.

Jiang et al. (2010) exposed shiitake mushrooms (*Lentinus edodes*) to UV-C light (4 kJ/m^2) and stored them in modified atmosphere packaging (MAP) for 15 days at 1 ± 1°C and 95% relative humidity plus 3 days at 20°C. UV-C treatment resulted in the maintenance of a high level of firmness during 15 days at low temperature and reduced the decrease in firmness during shelf-life. Furthermore, treated samples showed higher total flavonoids, ascorbic acid, and delayed the increases in both superoxide anion production rate and H_2O_2

contents. However, no clear treatment effects were seen in total phenolics contents. The treatment also increased the antioxidant enzyme activities of catalase, superoxide dismutase, ascorbate peroxidase and glutathione redutase throughout the storage period.

Baby spinaches

UV-C radiation applied at proper doses and to both sides of the baby spinaches could reduce microbial growth and extend shelf-life without adversely affecting the quality of fresh-cut baby spinach leaves. Escalona et al. (2010) applied UV-C (0, 2.4, 7.2, 12 and 24 kJ/m^2) radiation to both sides of baby spinach leaves in order to simulate a continuous production chain. The results showed effectiveness of initial microbial reductions in fresh-cut spinach at the beginning of storage using short exposure times and low radiation doses. Almost all the analysed microbial groups were reduced by UV-C radiation throughout the storage period. UV- C light significantly reduced *Listeria monocytogenes* growth in fresh-cut spinach for 14 days at 5°C. During the first 5–8 days, radiated leaves had lower *Salmonella enterica* and *Pseuomonas marginalis* counts compared to non-radiated samples. However these radiated leaves reached higher counts than control after 8 days of storage. A low UV-C dose (2.4 kJ/m^2) had a similar inhibitory influence on other microbial growth, compared to high doses such as 12 or 24 kJ/m^2. UV-C light was also effective at reducing psychrotrophic and Enterobacteria in fresh-cut spinach until 4 days at 5°C. Escalona et al. (2010) did not find the surface tissue damaged when it was inspected by electron microscopy, nevertheless they point out that it is possible that UV-C light caused some tissue damage of the spinach leaves, as measured by an increase in respiration.

Broccoli

Floret yellowing is a major limitation to shelf-life and broccoli quality. Therefore, suitable treatments are necessary to maintain quality levels until consumption. Some techniques to delay senescence have been investigated, including heat treatments, which effectively reduce yellowing among stored broccoli florets (Funamoto et al., 2002), chemical treatments such as 1-methylcyclopropene (Ku and Wills, 1999; Able et al., 2002) and ethanol vapour (Suzuki et al., 2004), low temperature (Starzynska et al., 2003) and controlled atmosphere storage (Yamauchi and Watada, 1998).

Results obtained by Costa et al. (2006) suggest that short UV-C treatments could be a useful non-chemical method to delay senescence in broccoli. Short UV-C treatments (4, 7, 10 and 14 kJ/m^2) delayed chlorophyll degradation in broccoli, with 10 and 14 kJ/m^2 doses showing the greatest delay. However, only 4, 7 and 10 kJ/m^2 doses reduced pheophytin accumulation. The UV-C treatment with a dose of 10 kJ/m^2 delayed not only chlorophyll *a* and *b* degradation but also the increase of chlorophyllase and chlorophyllperoxidase activity. In the case of Mg-dechelatase, higher activity was found immediately after the treatments, but after 4 and 6 days at 20 ◦C UV-C treated broccoli maintained lower Mg-dechelatase level than controls. The UV-C treatments also reduced tissue damage and disruption according to respiration rate and phenolic compound content. The antioxidant capacity was increased by UV-C treatments and this could be useful from the nutritional point of view.

Aiamla-or et al. (2009) reported that UV-B irradiation is effective in retaining the green colour of florets during storage. Those authors observed that, in general, broccoli florets retained more colour after UV-B irradiation than after UV-A. UV-B doses of at least 8.8 kJ/m^2 resulted in surface colour with a higher hue angle, as compared to those treated with 4.4 kJ/m^2 UV-B or without UV-B. They selected a UV-B dose of 8.8 kJ/m^2 for application to different broccoli cultivars (Pixel and Sawayutaka), harvested during the winter and early summer seasons. During storage, the 'Sawayutaka' exhibited a slower decrease in green colour of florets, when compared to the 'Pixel' cultivar. UV-B treatment delayed floret yellowing and chlorophyll degradation. Broccoli harvested in winter or early summer and irradiated with UV-B during storage at 15°C had a higher chlorophyll content and hue angle value than broccoli without UV-B treatment.

Peppers

UV-C treatment could be a useful way of reducing decay and maintaining bell pepper fruit quality, reducing chilling injury incidence and severity (Vicente et al., 2005). These authors observed that a dose of 7 kJ/m^2 avoided all symptoms of decay after 12 days at 10°C; treated fruit also kept firmer and maintained quality suggesting that the combined method (UV-C plus refrigeration at 0°C) could be a useful way of extending bell pepper postharvest life.

Strawberries

Allende et al. (2007) tested the effect of UV-C light, gaseous O_3, superatmospheric O_2 and CO_2-enriched atmospheres applied individually and in combination on the health promoting compounds and shelf-life of strawberries. The combination of different postharvest treatments had similar effects than individual treatments for 'Camarosa' strawberries. These authors concluded that all these postharvest treatments, which are commonly proposed to control microbial decay in strawberries, could have detrimental effects from a nutritional point of view, reducing phenolic and vitamin C content of 'Camarosa' strawberries.

Erkan et al. (2008), found that strawberry fruit illuminated with UV-C at different illumination durations and dosages, 1, 5 and 10 min and 0.43, 2.15 and 4.30 kJ/m^2, respectively, promoted the antioxidant capacity and enzyme activities and significantly reduced the severity of decay during storage at 10°C. UV-C illumination for 5 and 10 min showed the best results for enhancing antioxidant capacity expressed as oxygen radical absorbance capacity (ORAC) values after storage for 15 days among all the treatments. These treatments also enhanced the activities of antioxidant enzymes including glutathione peroxidase, glutathione reductase, superoxide dismutase, ascorbate peroxidase, guaiacol peroxidase, monodehydroascorbate reductase, and dehydroascorbate reductase. The nonenzyme components such as reduced glutathione and oxidized glutathione also were increased by UV-C exposure. All UV-C dosages increased the phenolic content of strawberry fruits as well. Total anthocyanin content increased during storage in all treatments. However, UV-C illumination showed little effect on the anthocyanin accumulation. Erkan et al. (2008) also found that all UV-C dosages retarded the development of decay, but 5 and 10 min UV-C illumination gave the best decay inhibition.

Exposure to UV-C delays fruit softening, one of the main factors determining fruit postharvest life. This softening delay might be caused by changes in the activities of enzymes and proteins involved in cell wall disassembly. Expansins, polygalacturonases, endoglucanases and pectin-methylesterases are cell wall proteins or enzymes involved in fruit softening. Pombo et al. (2009) analysed the effect of a UV-C treatment on strawberry fruit softening by the activity of polygalacturonases, pectin-methylesterases and endoglucanase, and the expression of a set of genes encoding for proteins and enzymes involved in cell wall degradation. UV-C treatment delayed fruit softening, and treated fruit showed higher firmness than controls even 96 h after irradiation. The irradiation modified the expression of the genes and the activity of assayed enzymes. In general, the expression of analysed genes was reduced a few hours after irradiation, while it increased afterwards to reach similar or higher levels than the controls. Therefore, the effect of UV-C irradiation on strawberry fruit softening could be related to the decrease of the transcription of a set of genes involved in cell wall degradation, during the first hours after treatment. The same authors (Pombo et al., 2011) also studied the induction of resistance to *Botrytis cinerea* in strawberry fruit, exposed to a hormetic dose of UV-C. The results obtained showed that pre-storage treatment of fruit with UV-C results in lower losses caused by diseases and decay, and the gene expression and enzymatic activity of a set of strawberry genes that are related to plant defence against pathogens were found to be modified in the treated fruit. Therefore, the reduction in strawberry fruit decay by UV-C treatment at harvest could be related to the increase in the transcription and activity of a set of enzymes and proteins involved in the defence against pathogens.

Blueberries

Perkins-Veazie et al. (2008) found that postharvest application on Blueberries (*Vaccinium corymbosum*, cvs. Collins, Bluecrop) of UV-C radiation, prior to storage, can decrease decay caused by ripe rot (*Colletotrichum acutatum*) in blueberries and may enhance antioxidant levels as measured by total anthocyanin, total phenolics, and ferric reducing antioxidant power. Stimulation of antioxidants by UV-C radiation appears to be dependent on cultivar and that weight loss and firmness was not affected by light treatment.

The levels of flavonoids in blueberries were found to increase after illumination with UV-C (Wang et al., 2009). Phytochemicals affected included resveratrol, myricetin-3-arabinoside, quercetin-3-galactoside, quercetin-3-glucoside, kaempferol-3-glucuronide, delphinidin-3-galactoside, cyanidin-3-galactoside, delphinidin-3-arabinoside, petunidin-3-galactoside, petunidin-3-glucoside, petunidin-3-arabinoside, malvidin-3-galactoside, malvidin-3-arabinoside, and chlorogenic acid (Wang et al., 2009). Significantly higher antioxidant capacity was detected in fruit treated with 2.15, 4.30, or 6.45 kJ/m^2 compared to the control fruit. UV-C dosage of 0.43 kJ/m^2 also increased phenolics and anthocyanins, but to a

lesser extent. The optimum doses of UV-C for enhancing phytochemical content in blueberries were 2.15 and 4.30 kJ/m^2. These data suggest that proper use of UV-C illumination is capable of modifying the phytochemical content of blueberries. Time course measurements of the effects of UV-C revealed that the strongest responses of fruit to UV-C treatment occurred instantly after the illumination and the effects diminished with time.

Eichholz et al. (2011) exposed blueberry fruits to UV-B radiation with low dosage and high dosage (0.27 and 0.54 kJ/m^2, respectively) with two adaptation times (2 or 24 h). The UV-B exposure increased the total phenolic content with a maximum at the higher dose, but the adaptation times did not significantly affect it. Content of volatiles metabolites, such as terpenes and ketones, increased at high dosage and low adaptation time. Content of alcoholic compounds, as degradation products of aldehydes, decreased after low adaptation time and increased after high adaptation time.

Apples

UV-C light exposure, if applied at mild intensity, was demonstrated to be an effective non-visible technology for food surface decontamination. Manzocco et al. (2011) studied the effect of UV-C light treatments at 1.2, 6.0, 12.0 and 24.0 kJ/m^2 relative to germicidal efficiency and changes in fresh-like appearance of fresh-cut apple. Independently of UV-C light intensity, all treatments showed the same germicidal effect with 1–2 log reduction in total viable counts. Treatments at an intensity exceeding 1.2 kJ/m^2 had detrimental effects over the cells of the surface apple tissue. On contrary, those authors observed that mild treatments could extend the shelf life of fresh-cut apple slices through various induced phenomena: surface decontamination, denaturation of oxidative enzymes, prevention of browning and off-flavours, and formation of a dried protective film which inhibits microbial growth and juice leakage. Due to very low depth penetration of UV-C light, this film was very thin and would not be perceived by consumer.

Hagena et al. (2007) investigated the effect of postharvest irradiation not only on the major classes of phenolic compounds, but also on other important health and sensory related properties in the peel and flesh of red, sun-exposed and green, shade-grown 'Aroma' apples. They were irradiated with a combination of visible light and UV-B radiation or visible light alone or covered with a black cloth during the entire experiment. The results suggest that postharvest irradiation in apples can be used to improve their health benefits and colour appearance without changing important taste-related parameters or causing damage to the fruit. The antioxidant capacity, total phenols and the content of anthocyanins, quercetin glycosides, chlorogenic acid and ascorbic acid increased upon postharvest irradiation. The accumulation of flavonols started earlier and increased to a level higher than the anthocyanins. A combination of visible light and UV-B radiation was the most effective irradiation treatment and the response was greatest for the peel of the shade-grown apples. The apple flesh showed no response to any of the irradiation treatments. Postharvest irradiation improved the apple skin colour, but did not influence the level of soluble solids or titratable acidity in the apples. No visible damage or substantial weight loss was found in the apples after the irradiation treatments.

Superficial scald is an apple fruit peel storage disorder characterized by necrosis of the first hypodermal cell layers of susceptible cultivars. Because sunlight exposure reduces scald, Rudell and Mattheis (2009) hypothesized that postharvest UV–vis irradiation will, likewise, reduce scald incidence. Granny Smith fruits, that had been covered with paper bags 57 days after full bloom to limit sunlight prior to harvest, were treated, after harvest, with light from white light fluorescent bulb and from fluorescent UV lamp. They observed that postharvest irradiation treatment reduced scald development. Even on the unexposed side of irradiated apples, where light exposure was limited, scald development decreased with increased light treatment duration.

Watermelon

When properly utilized, UV-C light is a promising sanitation tool for fresh-cut watermelon, keeping its overall quality, and possibly also to other fresh-cut fruit with delicate texture (Fonseca and Rushing, 2006; Artés-Hernández, 2010). The effects seem to be dependent on the UV-C doses.

Fonseca and Rushing (2006) investigated the influence of UV-C light (254 nm) treatments with that of common sanitizing solutions used for fresh-cut produce such as chlorine and ozone on the quality and microbial populations of fresh-cut watermelon (*Citrulus lanatus*). They obtained better results with ultraviolet (UV-C) treatments; the solutions of ozone and chlorine were not effective in reducing microbial populations and give poor quality. They achieved good results with 1, 4 kJ/m^2, higher doses did not show any effect in

microbial populations or even resulted in quality deterioration. They stress out the importance of an initial not high contamination level and of a complete surface exposure.

Artés-Hernández (2010) studied the effects of four pre-packaging UV-C illumination doses (1.6, 2.8, 4.8 and 7.2 kJ/m^2) on quality changes of watermelon cubes stored up to 11 days at 5°C. UV-C did not significantly affect the final gas partial pressures within modified atmosphere packages. UV-C decreased microbial counts just after illumination, and after 11 days at 5°C, mesophilic, psycrophilic and enterobacteria populations were significantly lower in UV-C treated watermelon. Slight changes in CIE colour parameters were observed. According to sensory quality attributes, control and low UV-C treated cubes (1.6 and 2.8 kJ/m^2) can be stored for up to 11 days at 5°C while the maximum shelf-life of moderate to high UV-C treated fruit was 8 days at 5°C. Low UV-C treated watermelon cubes preserved their initial lycopene content (2.8 kJ/m^2) or slightly decreased (1.6 kJ/m^2). UV-C radiation did not significantly affect the vitamin C content while catalase activity and total polyphenols content considerably declined throughout the storage period. However, total antioxidant capacity increased, independently of UV-C doses.

Traditional thermal treatments lead to colour and dynamic viscosity changes of watermelon juice, which are mainly catalysed by its intrinsic polyphenol oxidase and pectin methylesterase (PME), respectively (Rodrigo et al., 2006). Lycopene loss has also been reported during the processing and storage of watermelon (Perkins-Veazie and Collins, 2004). Non-thermal technologies which could avoid colour and dynamic viscosity changes and lycopene loss of watermelon juice are an option for the processing of the watermelon juice. Ultraviolet-C treatments are rapid and effective to inactivate the pectin methylesterase of the watermelon juice compared to the thermal and high pressure treatments in the same time and temperature Zhang (2011).

Pomegrenates

López-Rubira (2005) obtained unclear results on the effect of the UV-C radiation on the microbial growth of minimally processed fresh arils from the sweet 'Mollar of Elche' pomegranate (*Punica granatum*, Punicaceae), that were stored under modified atmosphere packaging (MAP) at 5º C. Some of the applied UV-C treatments reduced mesophilic, psychrotrophic, lactic acid and *Enterobacteriaceae* counts. However, microbial counts were not systematically reduced throughout the shelf life. In addition, UV-C treated arils showed higher bacterial counts in a few cases. Yeasts and moulds were unaffected by the UV-C treatments. So authors concluded that no benefits were found when different UV-C radiation doses were applied, and that the use of UV-C seems to be not justified for improving the shelf life of minimally fresh processed pomegranate arils in the conditions they studied.

Grapes for winemaking

Postharvest grapes can be treated with ultraviolet-C light to produce stilbene enriched grapes to be later used in a conventional winemaking process to obtain a red wine enriched in stilbenes (Guerrero et al., 2010). These authors observed that treatments promoted a maximum concentration in trans-resveratrol and piceatannol after pressing, but with a significant loss from grape to wine. A significant increase in both piceatannol and trans-resveratrol concentration (up to 26 times and 3.2 times higher than in control, respectively) was achieved in bottled wine. Regarding the oenological parameters, the wines obtained possessed good quality.

Papaya

Cia et al. (2007) investigated the effects of gamma and UV-C irradiation on the postharvest control of papaya anthracnose, the main postharvest disease in papaya fruit, caused by *Colletotrichum gloeosporioides*. UV-C irradiation was not able to protect the fruit, and moreover, all UV-C doses caused scald on fruit.

Mango

González-Aguilar (2007b) observed that UV-C treatment maintained better overall appearance, lower decay percentage and increased shelf life of fruit. These benefits correlated positively with higher levels of total phenols and flavonoids, enzymatic activities of lipoxygenase and phenylalanine ammonia-lyase. They conclude that UV-C treatment can be a good alternative to increase the shelf life in optimal conditions of mango 'Haden'.

Citrics

UV-C light treatments for 10 min significantly reduced green mold of Satsuma mandarins, caused by Penicillium *digitatum* (Pers.) Sacc., although, this treatment caused injuries that appeared as burning and browning on the fruit surface (Kinay et al., 2005). Irradiation with UV inhibited decay in inoculated citrus fruit; it has been shown that this

treatment elicits the synthesis of the phytoalexins scoparone and scopoletin (Ben-Yehoshua, 2003).

Tahitian lime (*Citrus latifolia* Tan.), originated in South-East Asia, are usually picked and marketed while the peel is still green. Under ambient conditions, the lime fruit become yellow within a few days, which decrease their commercial value. Normally, the peel of lime fruit is green due to the presence of chlorophyll pigment (Grierson and Ting, 1978), located in the flavedo of the peel. Peel yellowing of lime fruit is attributed to the degradation of chlorophyll (Drazkiewice, 1994). In lime, the postharvest maintenance of the green colour in the peel is required to obtain premium prices. Srilaong et al. (2011), in a study, focusing on the effects of UV-B, on physical and biochemical changes in relation to chlorophyll degradation, mature green lime fruit were irradiated with UV-B light and stored them at 25º C in darkness. The authors concluded that treatment effectively suppressed chlorophyll degradation in mature green lime during storage, so they suggested that UV-B irradiation is a usable method for prolonging the postharvest life of lime fruit.

Conclusion

Water treatment based on UV radiation is a well-established technology. With few exceptions, in general, results confirm that UV radiation presents potential to become widely used through direct application on vegetables and fruits to obtain two distinct classes of beneficial effects: to reduce microbial population in these products; and, through applications of low, hormetic doses, to elicit some desirable responses in these products to improve their defence against molds, improve the content of components with beneficial effects for health, extend the shelf-life, keep or even improve the sensorial characteristics. These beneficial effects depend on the dose, application moment, fruit or vegetable species and cultivar, and exposed area. The scaling to commercial implementation needs to be evaluated.

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