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Application of Ultraviolet Light during Postharvest Handling of Produce: Limitations and Possibilities

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ABSTRACT

The use of ultraviolet (UV) light for improving the quality and safety of whole and fresh-cut fruits and vegetables is reviewed. Ultraviolet-C (UV-C) is non-ionizing radiation that does not penetrate beyond surfaces and is generally regarded as a contact germicide. However, UV-C may induce resistance to various stress factors in tissue via hormesis (initiation of a positive reaction by a low dose of radiation). In some studies, UV-C light treatments have shown potential for controlling various post harvest fungal diseases, an effect often accompanied by delay of senescence. More recent studies suggest that UV-C can alter nutritional composition of some fruits and vegetables, revealing its potential as a tool to develop fresh functional products. Treatments that include UV-C in combination with other sanitizing agents appear to be particularly effective in reducing populations of human pathogens, but little is known about the effects of hurdle sanitizing systems on other aspects of the product's quality including nutrient content. Although it is well known than plants respond to UV-A and UV-B, examination of these wavelengths for postharvest applications has been scarce. Overall, UV is a promising technology for postharvest disease control and microbial population reduction in some operations; provided that economically feasible means of irradiating fruits and vegetables on a large scale are identified.

Keywords: fruits, secondary metabolism, shelf life, vegetables, wavelength

CONTENTS

NEED FOR A NON-CHEMICAL SOURCE

A number of chemical options with feasible implementation in different steps encountered during production and handling of perishable horticultural crops have been reported. The conventional methods, involving bactericidal (e.g. chlorine) and fungicides (e.g. oxazoles) are, however, of concern, since many pose a threat to human health (Wilson *et al*. 1991), which has motivated research aiming the identification and/or development of alternatives.

Emerging technologies to reduce proliferation of diseases of produce have been examined, including antagonistic organisms, natural anti-fungal substances and natural defense mechanism such as ultraviolet-C (UV-C) light (Mari and Guizzardi 1998). Treatments with UV-C light (200-280 nm range) potentially present several advantages to the produce industry as it does not leave a residue, have no legal restrictions, does not require complex equipment (Yaun *et al*. 2004), requires no subsequent removal of moisture (Fonseca 2006) warranting more in-depth analyses for its use in the whole and fresh-cut produce industry.

The objective of this report was to review the current knowledge about the use of ultraviolet light for extending the shelf life of intact and fresh-cut produce.

HORMESIS EFFECT

Two possible reasons of why storage rot decay of fruits and vegetables is reduced by UV-C treatments have been suggested. First, is the germicidal effect on pathogens found on the surface of the host and secondly, the induced resistance by hormesis in the tissue of fruits and vegetables (Stevens *et al*. 1999). Additionally, UV-C irradiation may produce delay in the appearance of climacteric phase in irradiated climacteric fruits (Maharaj 1999), which in turn affects the onset of fungi symptoms.

Hormesis was first defined by Luckey (1980) as the stimulation by low quantities of any potentially harmful agent. This author proposed a mechanism for hormesis, suggesting that a low dose of UV could inflict repairable damage to DNA, and that this slight trauma would activate repair mechanisms for radiation-induced DNA damage. This suggests that sub-lethal radiation may stimulate vital processes inside the cells and create a positive change in the homeostasis of a plant (Shama and Anderson 2005). Authentic hormetic responses in fruits are clearly distinct from the direct effects of UV on surface-associated pathogens.

The treatment of produce with low UV (0.5 kJm^{-2}) results in the synthesis of a number of anti-fungal compounds

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in the fruit or vegetable (D'hallewin *et al*. 2000). Shama and Anderson (2005) revised the hormetic effects of UV on different fruits and found that with the exception of cactus pears and cherries, positive results were obtained in all the studies conducted with the UV treatment. Produce mentioned as benefited from application of UV treatment included apple, grapefruit, kumquat, lemon, mango, orange, peach, pepper, strawberry, tangerine and tomato. In several cases, the synthesis initiated by the UV treatment continues to occur for several days.

The optimal UV dose for maximum hormesis effect ranged from 0.125 to 9 kJm^{-2} to control growth of plant pathogens such as *Botrytis cynerea* in grapes (Nigro *et al*. 1998) and *Penicilium digitatum* in oranges (D'halewin *et al*. 1999). Stevens *et al*. (2005) exposed apples, peaches and tangerines to UV-C light in two ways, directing light to stem ends or by rotating the fruit. When stem end were irradiated with fruits in a stationary positions the results were equally or better than when fruits were rotated, revealing a clear effect on tissue that was not directly exposed to irradiation.

Plants' metabolism activates both non-enzymatic antioxidants and enzymatic scavengers such as superoxidase dismutase (Maharaj 1999) in response to the damaging effects of free radicals (Wellman 1976). It has been suggested that UV-C irradiation may induce antioxidants that counteract the effect of DNA and free radical damage associated with aging and senescence (Maharaj 1999). UV-C extended shelf life of tomato, and particularly retarded decay and the loss of fruit firmness by affecting cell wall-degrading enzymes such as polygalacturonase, pectin methyl esterase, cellulose, xylanase β-D-galactosidase and protease (Barka *et al*. 2000). The defense response induced with UV treatments, involving reduction in the concentration of aliphatic esters and production of terpenoid phytoalexins, have been suggested to screen cantaloupe melon cultivars for disease resistance (Lamikanra *et al*. 2002). Treatment of UV-C reduced germination, germ tube elongation and growth of *Fusarium solani* in sweetpotato compared to untreated roots (Stevens *et al*. 1999). This effect was associated with enhancement of the activity of phenylalanine ammonia-lyase (PAL) enzyme and increased accumulation of phenolics (Stevens *et al*. 1999).

The hormetic effect seems to be more easily observed with whole fruits and when the radiation targets pathogens of the skin. When UV-C has been used to irradiate fresh-cut watermelons complete exposure of the surface was needed to achieve a significant effect (Fonseca and Rushing 2006). However, processing melons under simultaneous UV-C light induced a hypersensitive defense response that resulted in increased accumulation of ascorbate peroxidase, in comparison with an untreated control and with a post-cut UV-C treatment (Lamikanra *et al*. 2005) suggesting a quick response of the tissue to UV-C treatment to counteract the stress effect produced by cutting.

DIRECT KILLING STEP

Reported control of fruit rots with UV-C light has been associated to an induced resistance to the pathogens or to a direct germicidal effect or to both (Stevens *et al*. 1998). Direct fungal inactivation occurs once a sufficiently high UV dose has been accumulated by the organism. If inactivation of this kind were to occur, it would be limited solely to the surface of the fruit or leaf since UV has extremely limited penetration into solids (Gardner and Shama 2000). Different survival patterns in bacteria have been successfully described in terms of the Wibullian distribution. Such model evidence differences between survival patterns that is not possible to demonstrate using traditional survival models (Schenk *et al.* 2007).

Creation of pyrimidine dimers, particularly between adjacent thymine bases, is the most common type of photochemical damage induced by UV-C light (Harm 1980). Eischeid and Linden (2006) determined UV dose response curves on both log reduction in *Escherichia coli* colony-forming units and endonuclease-sensitive sites per kbDNA for monocharomatic 254-nm low-pressure (LP) UV, polychromatic medium-pressure (MP) UF, 228 and 289-nm UV irradiation. The authors observed an agreement of bacteria reduction with the absorption spectrum of pyrimidine bases in DNA confirming that the formation of pyrimidine dimmers in genomic DNA is the primary reason for UV inactivation of *E. coli.*

Bacterial spores are generally more resistant to UV-C treatment than bacteria in a vegetative state. Likewise, cells in exponential growth are commonly less resistant than cells in the stationary phase (Allende and Artes 2003). Growth of lactic acid bacteria on lettuce was stimulated following UV-C treatment, probably due to higher relative resistance and lack of competing microbes. UV light at a dose exceeding $9mWcm^{-2}$ resulted in a 2-log reduction in microbial populations on lettuce and tomatoes and 3-log reduction in microbial populations on apples (Yaun *et al*. 2004).

Allende and Artes (2003) found that UV-C radiation decreased growth of psychrotropic bacteria, coliform and yeast but at 8.14 kJm^{-2} (highest dose in the study) the lettuce became shinier. Stimulation of the activity of lignifying enzymes was also observed.

At lower dose, browning and growth of lactic acid bacteria was reduced, probably due to declined growth of competitive bacteria. Tissue brightness was also reported in lemons (Ben-Yehoshua *et al*. 1992), which was attributed to enhancement of lignification in protection against UV-C rays.

LIMITATIONS TO CONSIDER

The major weakness of UV light as germicidal agent is related to its inability to go through physical barriers. UV-C radiation only penetrates 50-300 nm into tissue (Jagger 1965). Thus, to achieve direct killing of bacteria complete surface exposure is needed to stimulate defense mechanisms against particular organisms. For fresh-cut watermelon, complete surface treatment was necessary to decrease microbial counts (Fonseca and Rushing 2006). Occlusion of the light path with water or with tissue negatively impact efficacy (Bank *et al*. 1990). It has been suggested that UV-C light performance is reduced when fruits are previously subjected to waxing, since the coating shield bacteria from the UV rays (Yaun *et al*. 2004).

One of the main difficulties with UV application of produce is assuring a dose to all products. When UV has been used to treat water the recycling of fine catalysts from the solution is required, which is an inconvenient and expensive process. This however, may be avoided in stationary photoreactors in which photocatalyst particles are immobilized onto a fixed surface such as the reactor wall, fiber mesh, glass or ceramic beads that are held in fixed positions in the photoreactor (Cooper 1989; Anderson 1991; Sato 1992). In this regards, narrow diameter lamp that allows increased surface area for catalyst coating per unit reactor volume was reported to improve efficiency by 6.9 and 2.6 times in comparison with classical annular and slurry reactors respectively (Ray and Beenackers 1998).

Another potential limitation concerns is the re-contamination or re-growth of certain microorganisms at a higher rate than in untreated produce. Lopez-Rubira *et al*. (2005) obtained mixed results when treating pomegranate arils treated with UV-C, obtaining in some cases UV-C treated arils with higher microbial counts. It is possible that regrowth of microorganisms during postharvest handling occurred. Development of resistance to bacteria growth has not been reported.

UV-C light may have different effects depending on the bacteria strain (Bank *et al*. 1990; Jacobs and Sundin 2001). Different bacteria may have certain preferences for attachment, which can subsequently affect UV-C effect. For example, *E. coli* O157:H7 was found more on cut edges of lettuce, whereas *Salmonella typhimurium* was attached equally

to either the cut edge or the intact surface (Takeuchi *et al* 2000). Clearly, the surface topography is a major factor affecting the decontamination efficiency of UV-C.

When *Salmonella* spp. or *E. coli* O157:H7 were inoculated, postinoculation UV-C treatment had no antimicrobial effect on lettuce, but decreased the pathogen population substantially on tomato (a maximum log reduction of 2.19 log of *Salmonella* spp. at 0.24 kJ m^{-2}) and even more on apples (approximately 3.3 logs reduction of *E. coli* O157:H7 at 0.24 kJm^{-2}; Yaun *et al*. 2004).

Photo reactivation, a phenomenon that involves the recover of inactivated pathogens from photochemical damage, is another limitation to consider. Out of 43 spores of *Bacillus* 19 showed resistance to UV-C after exposure to 1,000 Jm^{-2} at 254 nm using a low pressure mercury lamp (Newcombe *et al*. 2005). Oguma *et al.* (2002) suggested medium pressure (200-230 nm) UV lamp source as an alternative to the low pressure UV lamp (253.7), since it was more effective in repressing repair of *E. coli*. However, photo-repair from inactivation of *Mycobacterium terrae* was found to be approximately 0.5 logs in less than 30 minutes using different UV-C lamp systems (Bohrerova and Linden 2006). Photo reactivation is a concern with bacteria, but not with viruses, although it is known that resistance to UV-C differs among types of virus (Nuanualsuwan *et al*. 2002). In this study, the decimal inactivation doses of UV for feline calicivirus, hepatitis A virus, poliovirus type 1 were 47.85, 36.50 and 24.10 mW s cm^{-2} respectively.

UV-C light may compromise quality of produce under certain conditions (Ben-Yehoshua *et al*. 1992; Allende and Artes 2003; Fonseca and Rushing 2006). At the dose (8.14 kJ m^{-2}) that could reduce mold growth, in part due to increased growth of lactic acid bacteria, lettuce tissue became brighter, which was attributed to segregation of wax by the lettuce tissue in a protection response to UV-C (Allende and Padilla 2003). However, there are cases where side effects have become beneficial. Liu *et al*. (1991) observed that ripening of tomatoes was delayed, which subsequently prolonged the shelf life. Although increased transpiration may occur (Allende and Padilla 2003) as a result of UV-C treatment in pear, increased weight loss was not observed with the UV-C treatment (Piga *et al*. 1997). Postharvest UV-C treatments have been suggested as commercial method to identify pinto beans varieties prone to rapid darkening (Junk-Knievel *et al*. 2007).

Higher levels of sugars and lower levels of organic acids were observed in mangoes treated with UV-C light, however, at the optimal dose no differences were found (González-Aguilar *et al*. 2001). The optimal dose produced higher levels of agmatine, putrescine and tyramine, in agreement with another study with tomato (Maharaj 1999). The produced polyamines have radical scavenging properties and can interact with phospholipids to stabilize the bilayer surface and retard membrane deterioration (Drolet *et al.* 1986). UV-C produces a considerable decrease in the concentration of esters and synthesis of the phytoalexin terpenoid compounds, β-ionone and geranylacetone (Lamikanra *et al*. 2003). Likewise, in pineapple UV-C radiation caused a considerable decrease in the content of esters (Lamikanra and Richard 2004). The response of plants or harvested products to UV-C light may be dependent in previous conditions. For example, research with seedless grapefruit have shown (Droby *et al*. 1993) that inoculated fruit harvested in February required approximately double the UV-C irradiation dose (8 kJm^{-2}) to induce maximum resistance against *P. digitatum* in comparison to fruit harvested in November. The effect of a previous factor may be connected with the metabolic pathways affected by UV-C. Two examples of this are salt treatments and UV-C light, which appear to affect the same cell structure. The effect of a UV-C hormic dose involves decrease of the activity of cell wall-degrading enzymes (Barka *et al*. 2000) while also stimulating the formation of phenolic and lignin deposition in cell wall (Charles *et al*. 2008). Moreover, it is known that salt stress affects cell wall extensibility (Nonami *et al*. 1995) and increases formation of cell wall-bound phenolics and deposition of lignin (Fan *et al*. 2006). The vitamin C pathway has also been suggested to be associated with cell wall metabolism (Wolucka *et al*. 2007). It is possible that a previously induced reinforcement of the cell wall through salt stress alters the type of response of the harvested tissue to UV-C light (Kim *et al*. 2008).

MISCELLANEOUS USE IN PRODUCE APPLICATIONS AND EMERGING OPPORTUNITIES

UV-C radiation may be used for processing plants in many ways: as sanitizer food contact surfaces, for sterilization of water used for rinsing in food or process plants, for purification of air in food preparation area, and disinfection of plastic packages (Bintsis *et al*. 2000). Disinfection is a primary process for inactivation of waterborne pathogens to guarantee the safety of users and of the environment downstream from water outfalls. In water, UV radiation can effectively and rapidly inactivates pathogens by the transfer of electromagnetic energy from a mercury arc lamp, through photochemical reaction with their nuclei acids (Slade *et al*. 1986). UV-C light and heat killed *Legionella pneumophila* in water 5 times faster than chlorine at 18-40 mgL^{-1} and ozone at 1-2 mgL^{-1} (Muraca *et al*. 1987). UV-C light inactivated feline calicivirus (FCV), hepatitis A virus (HAV) poliovirus type 1 (PV1) and two small coliphages (Nuanualsuwan *et al*. 2002).

Mixed results have been obtained when assessing the efficiency of UV applications for reducing airborne microorganisms, which partially was attributed to the lack of engineering design parameters (Kowalski and Bahnfleth 2000). Results from Peccia and Hernandez (2004) revealed that UV inactivation responses for bacteria suspended in water cannot be used to estimate UV dose response in unsaturated air (50% Relative Humidity, RH). In this study, at 50% RH the airborne UV inactivation rates were two times greater than in saturated air (95% RH)

UV-C may be used to enhance nutrients in harvested produce. The resveratrol content in UV-C irradiated grapes was 10-fold higher than that of untreated Napoleon grapes, a finding that has become a commercial patent (Cantos *et al*. 2001). This response may influence by grape variety (Cantos *et al*. 2002). Authors estimated that resveratrol from UV-treated grapes is more than that obtained from seven glasses of red wine. In some cases the dose applied could produce reduction in phenolic composition. UV-C treated strawberries showed lower phenolic concentration, which was attributed to the decrease in procyanidins (Allende *et al*. 2007).

UV-C has shown multiple effects on extending shelf life of various fruits and vegetables. Reduction of chilling injury appears to be an additional benefit of using UV-C light. UV-C treatments reduced chilling injury incidence and severity of bell pepper, evidenced by lower electrolyte leakage, respiration rate and phenolic content when exposed to low temperature storage (Vicente *et al*. 2005). Chilling injury was not developed in mangoes that were irradiated with UV-C (González-Aguilar *et al*. 2001). Similarly, peaches that were subjected to UV-C irradiation showed significantly lower chilling injury levels than control peaches (Gonzalez-Aguilar *et al*. 2004). Alleviation of chilling injury in bell pepper fruit was also achieved with UV-C treatment (7 kJ m^{-2}). Sweet potatoes are reported with greater starch when treated with UV-C irradiation (Stevens *et al*. 1990). The breakdown of chlorophyll in broccoli florets was reduced with at 7kJ m^{-2} (Costa *et al*. 2006))

Very little has been reported on the use of other wavelengths associated with UV-B (280-320 nm) and UV-A light (320-400 nm) on postharvest operations. It was observed that UV radiation accelerate plant's growth when the overall visible light is above or below certain thresholds (del Corso and Lercari 1997). Supplemental UV-B and UV-A increased carotenoid levels in green leaf lettuce, whereas the same treatments reduced the amount of carotenoids in red-leaf

Table 1 Selected reports on reduction of microorganisms on various fruits and vegetables.

UV-C dose rate (kJm^{-2})	Produce	Microorganisms targeted	Reduction (log_{10} CFU)	Key observation	Reference
24	Apples	*E. coli* O157:H7	3.3		Yaun *et al.* 2004
24	Tomato	*Salmonella* spp.	2.19		Yaun *et al.* 2004
24	Green leaf lettuce	*Salmonella* spp. and *E. coli* O157:H7	2.65 and 2.70		Yaun *et al.* 2004
8.14	Lollo Rosso lettuce	Psychrotrophic bacteria	1.0 on day 6	Segregation of wax was produced	Allende and Padilla 2003
2.83	Cantaloupe pulp	Mesophilic bacteria	5.5 (when processing was done under UV light)	Reduction was 3 log_{10} when UV application was implemented after cutting	Lamikanra *et al.* 2005
0.56-13.62	Fresh cuts arils from pomegranates	Mesophilic bacteria	0.4 on day 3	Control had lower counts after day 6	Lopez-Rubira *et al.* 2005
1.4-6.9	Watermelon pulp	Mesophilic bacteria	0.8-1.3	Higher dose produced quality deterioration	Fonseca and Rushing 2006
1.18-7.11	Red leaf lettuce	Enteric bacteria	0.5-0.7	Shelf life of the product was improved by 1-3 days	Allende *et al.* 2006
61.2	Radish sprout	*Shigella sonnei*	0.45	A 2 log_{10} reduction was obtained when UV was applied in combination with 0.1%Hydrogen peroxide	Rajkowski 2007
0-87	Pear pulp and pear skin	*Listeria innocua*, *L. monocytogenes*, *Escherichia coli*, *Zygosaccharomyces bailli*	2.6-3.4 for pear pulp and 1.8-2.5 for pear skin	Inactivation kinetics fitted a Weibullian distribution	Schenk *et al.* 2007

lettuce (Caldwell and Britz 2006). The authors attributed the results to light-dependent changes in phenolic phytochemical levels at the leaves epidermal layer. Red-leaf lettuce produces higher levels of phenolics, however, the induction in the epidermal tissue may have reduced the overall photoprotective requirement for chloroplast carotenoids. UV-A (320-400 nm), which constitutes over 90% of the solar UV radiation was lethal to various *Saccharomyces cerevisae* mutants which were not capable of repairing (Kozmin *et al.* 2005), however, bacteria such as *Bacillus* sp was resistant, unless subjected to the whole UV spectrum (Newcombe *et al*. 2005). UV-A did not affect fruit ripening, incidence of physiological disorders superoxide dismutase activity and fruit temperature of tomato (Maneerat *et al*. 2003).

Red clover treated with UV-B was suggested increased levels of isoflavones, caffeic acid and flavonols (Swinny and Ryan 2005). On the other hand, when peanut plants were irradiated with UV-B the composition of bacterial community was affected, notably observing the proliferation of bacteria such as *Bacillus coagulans*, *Clavibacter michiganensis* and *Curtobacterium flaccumfaciens* (Jacobs and Sundin 2001).

UV-C has been suggested as an ideal second treatment to fungi (Stevens *et al*. 1997) and pathogenic bacteria. UV-C in combination with heat treatments enhanced benefits of applying each treatment separately and was also found to extend the shelf life of strawberry (Marquenie *et al*. 2002; Pan *et al*. 2004). Combined treatments of hydrogen peroxide and UV-C light results in higher microbial reduction than the single treatments alone (Hadjok *et al.* 2008).

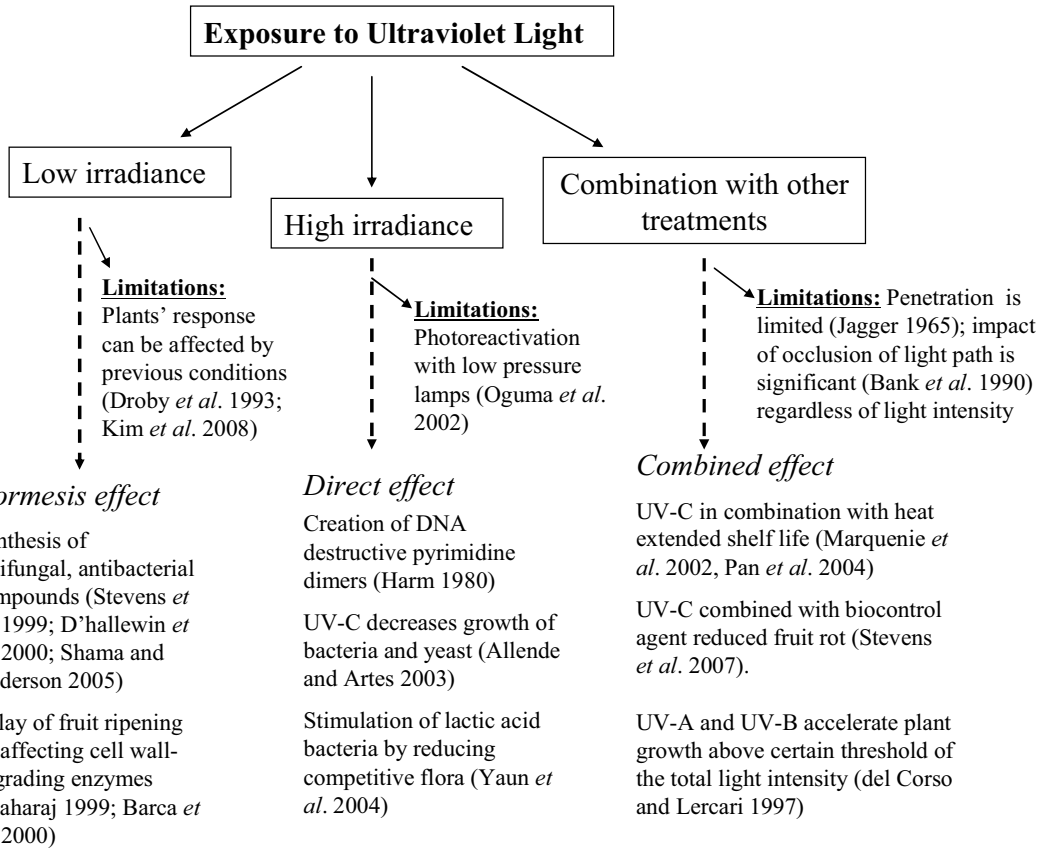

Fig. 1 Summary of effects triggered by posthavest UV irradiation in fruits and vegetables.

Brown rot caused by *Monilinia fructicola* of peach was reduced from 100% incidence to 12% with UV-C light in combination with the biocontrol agent *Debaryomyces hansenii*, a performance that was similar with post harvest fungicides (Stevens *et al*. 1997).

One potential benefit not yet well exploited is related to the UV potential for accelerating the degradation of pesticide residues from harvested produce. It is known that UV-A and UV-B plays an important role in the photodegradation of pesticides (Dillon 1986). UV radiation exposure in combination with temperature at 37°C significantly enhanced volatilization, mineralization and degradation of coumaphos (Jindal *et al*. 2007).

An alternative to mercury lamps as an intense source of UV radiation is the pulsed xenon arc, or xenon flashlamp. The xenon pressure is usually in the range 50-100 kPa, and under pulsed conditions, a xenon flashlamp emits several strong UV lines suitable for the inactivation of viruses (Lamont *et al*. 2007) and a range of bacteria (Rowan *et al*. 1999). Low pressure xenon-filled flashlamp provides a high-intensity beam of polychromatic pulsed light, with an emission that range from UV (all wavelengths) to infrared (Lamont *et al*. 2007). Reductions of near 4 and 3 $\log_{10}$ of *Salmonella* sp. and *E. coli* O157:H7 were observed in blueberries when used UV pulsed treatments (Bialka and Demirci 2007). Interestingly, it was revealed that the sanitizing efficiency of UV pulses on food products depends on the food's composition. Proteins and oil decrease the effect whereas carbohydrates and water have shown variable results depending on the microorganism (Gomez-Lopez *et al*. 2005). The application of pulsed UV-light warrants more research.

CONCLUSIONS

The effect of UV light applied during postharvest on fruits and vegetables may be diverse depending on dose, previous conditions/treatments and/or surface subjected to irradiation (**Fig. 1, Table 1**). It has been shown that fruits and vegetables subjected to UV-C can develop resistance to various stress factors including fungal and environmental factors via hormesis. UV-C can increase nutritional composition of some fruits and vegetables, revealing its potential as a tool to develop functional fresh products. Treatments that include UV-C in combination with other sanitizing agents appear to be particularly effective in reducing populations of human pathogens, but little is known about the effect of hurdle sanitizing systems on other aspects of the product's quality including nutrient content. More information needs to be generated to determine the impact of using UV-A and UV-B during postharvest, particularly when utilized under pulsed conditions with xenon flashlamps. Overall, UV is a promising technology for postharvest disease control and microbial population reduction in some operations; provided that economically feasible means of irradiating fruits and vegetables on a large scale are identified.

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