UV treatment of fresh fruits and vegetables for improved quality: a status report

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Abstract

Purpose of review: Over the past 20 years, ultraviolet (UV) hormesis has been evaluated as a postharvest treatment for fresh fruits and vegetables. Results from several independent research teams highlight the potential of this new technology. The objectives of this review are to present an overview of UV hormesis in postharvest crops and to characterise their responses to this physical stressor. Considerations related to future directions for the application of UV treatment are also discussed.

Findings: UV treatment applied to fresh fruits and vegetables at defined low effective doses, termed hormic or hormetic, results in a beneficial response in treated plant organs. UV-treated horticultural crops show improved resistance to disease development that is primarily related to the induced synthesis and accumulation of phytoalexins, as well as other defence mechanisms. UV treatment also favourably affects the evolution of several quality parameters in treated commodities. For model commodities such as grape, citrus and strawberry, results have been presented on the UV enhancement of bioactive compounds known to be beneficial to human health and well-being.

Directions for future research: UV treatment is likely ready for commercial application. However, any attempt to develop an online apparatus must address crop specificity and the range of factors that affect hormetic responses. Future multidisciplinary research should support the development of effective technological designs applicable to particular postharvest systems.

Keywords: ultraviolet; hormic; hormetic; disease resistance; senescence; bioactive phytochemicals

Abbreviations

6-MM	6-Methoxymellein
C_2H_4	Ethylene
PAL	Phenylalanine Ammonia-lyase
PR	Pathogenesis-related
RH	Relative Humidity
UV	Ultraviolet

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Introduction

Fruits and vegetables are an essential part of the human diet. They not only add flavour, colour and variety to the diet but also supply essential nutrients. They are also a major source of antioxidants, anticarcinogenic phytochemicals and complex carbohydrates, which are important for human health and well-being. Consumers are increasingly aware of the relationship between diet and health, and the trends in consumer purchasing patterns indicate a growing interest in fruits and vegetables, which offer health benefits over and above their nutritional value. Consumers are also demanding products free of pathogens, microbial toxins and chemical residues.

Fruits and vegetables are highly perishable due to their susceptibility to fungal infection, tissue senescence and transpiration. As a result, the horticulture industry is constantly seeking safer and more effective preservation techniques for

fresh produce in order to extend shelf-life, maintain resistance to diseases and retain beneficial phytochemicals.

Ultraviolet (UV) treatment of fresh produce is considered an alternative to chemical approaches that has great potential for controlling postharvest diseases [1–3]. Although UV light is generally harmful to living systems at high doses, at low doses it induces disease resistance in horticultural crops, slows ripening and maturation rate, and improves customary quality attributes. In specific cases, UV light also improves phytochemical content. This biological phenomenon is known as hormesis, where a low dose of a harmful physical or chemical agent stimulates beneficial responses in biological systems [4, 5]. The beneficial doses of the stressors are termed hormetic [6] or hormic [1] doses.

The objectives of this review are to present an overview of the UV hormesis phenomenon in postharvest horticultural crops and the responses of such crops to hormetic UV treatment, and to identify future prospects for the adoption of this new technology by the fresh produce industry.

UV hormesis in horticultural crops

Harvested plant organs intended to be stored for subsequent consumption in the fresh state have various morphogenetic origins. They also differ in their postharvest behaviour and in their ability to respond to different postharvest practices and treatments. Differences in sensitivity to UV light also exist among species in field-grown plants. Therefore, it is not surprising that postharvest plant organs react differently to different doses of UV-C applied to prolong their postharvest life. Studies by several research groups have shown the existence of a defined level of UV treatment that stimulates beneficial responses in a variety of crops. The reported hormetic UV doses for treatment of fruits and vegetables range from 0.125 to 9 kJ/m^2. The lowest and the highest hormetic doses were reported for table grape [7] and orange [8], respectively. For most commodities, a single dose is characterised as hormetic, although for some a range of doses is considered beneficial. The dose required for a specific response also differs between crops. For example, the hormetic dose required for controlling a fungus in apple [3] was different from the dose required in grapefruit [8]. In addition, seasonal differences (eg, for grapefruit) [9] and varietal differences (eg, for sweet potato) [10] affected hormetic doses. In some instances, only a minor difference in the hormetic dose requirement was found by two independent groups (eg, in mature green tomato) [11, 12 vs. 13].

Disease control

The phenomenon of disease resistance

Effective control of several common pathogens that cause decay of postharvest crops was achieved by pre-storage treatment with defined hormetic UV doses [14]. Both fungal and bacterial rots were reduced by pre-storage application of the hormetic UV treatment. Several factors can affect disease

control in UV-treated commodities. Different hormetic doses were necessary for controlling different pathogens on the same produce [3, 13]. Maturity and physiological age also affected the responsiveness of the treated tissue. Tomato fruits irradiated at the mature-green stage showed higher resistance than fruits treated at the breaker stage [13, 15]. The level of resistance induced by UV-C was also attenuated in older carrot roots compared with fresh roots [16]. Varietal differences were also observed by Stevens *et al.* [10], who reported that the hormetic dose for the sweet potato cultivars Jewel and Carver was 4.8 kJ/m^2 versus 3.6 kJ/m^2 for Georgia Jet. Droby *et al.* [9] found that a higher dose was required for maximum resistance against *Penicillium digitatum* as the season progressed. The development of disease resistance appeared to be a gradual process, as suggested by the results of Charles *et al.* [17], Mercier *et al.* [18], Droby *et al.* [9] and Ben-Yehoshua *et al.* [19]. The latter two studies reported that two citrus fruits (lemon and grapefruit) were as sensitive to green mould as the control when inoculation was performed immediately or a few hours after UV treatment. The maximum level of resistance in citrus fruits was observed 48 h after treatment [9, 19]. In carrot slices, the establishment of the induced resistance proceeded at a slower rate and was observed only after 7 days, presumably because of the lower storage temperature [18]. The latency period was even longer in whole carrot roots, in which the resistance response to *Botrytis cinerea* was observed only after 25 days [16]. In tomato fruits, resistance to *B. cinerea* was evident within 72 h after UV treatment, preceded by a period of high sensitivity compared with the control [20]. Expression of the induced disease resistance was also affected by storage temperature. Lower temperatures, 1ºC versus 4ºC in carrot slices [18] and 6ºC versus 11, 17, 20 or 25ºC in grapefruit [9], were more effective in maintaining the resistance response.

The mechanisms of disease resistance

The observed reduction of disease incidence in UV-C-treated fruits and vegetables does not for the most part seem to be due to surface sterilisation of the tissue or a germicidal effect on the pathogens [21], although some decontamination could occur [19, 22, 23]. The maintenance of the juvenile state may explain, in part, the resistance of UV-treated tissue to pathogenic fungi.

It is likely that UV treatment triggers more than one defence mechanism, but there is more information available on the enhancement of preformed antifungal compounds and on the elicitation of phytoalexins, which are low-molecular-weight secondary metabolites with antibacterial and antifungal activities. The resistance of immature tomato fruits to *B. cinerea* is attributed to the presence of the glycoalkaloid tomatine. In UV-treated tomato, higher levels of tomatine were detected over a storage period of 96 h after treatment [24]. A low dose of UV-C was shown to induce various classes of phytoalexins in several postharvest commodities. Several studies present solid evidence of a positive correlation be-

tween phytoalexin accumulation and the observed disease resistance. In carrot slices and roots, the accumulation of the isocoumarin phytoalexin, 6-methoxymellein (6-MM), was strongly correlated with the development of resistance to *B. cinerea* and *Sclerotinia sclerotiorum* [16, 18]. In citrus fruits (grapefruit, kumquat, lemon, orange) resistance to *Penicillium digitatum* and *Penicillium italicum* was linked to the accumulation of scoparone or scopoletin [8, 9, 19, 21]. The expression of resistance in tomato fruits to *B. cinerea* was concomitant with induction of the phytoalexin rishitin in the UV-treated tissue [20, 25]. The phytoalexins isalexin, S-(-)-spirobrassinin, 1-methoxybrassitin, brassicanal C and caulilexins A–C were detected in cauliflower subjected to a low dose of UV-C. The antifungal activities of caulilexin A, caulilexin C and brassicanal C, three phytoalexins induced by an unspecified UV-C dose, were evaluated in bioassays with *Leptosphaeria maculans*, *Rhizoctonia solani* and *Sclerotinia sclerotiorum* [26]. From these bioassays, caulilexin A was characterised as the metabolite with the highest antifungal activity against *R. solani* and *S. sclerotiorum*. Resistance of table grape to *B. cinerea* and other pathogens both during growth and at the postharvest stage has long being associated with the UV-C–inducible phytoalexins resveratrol, ε-viniferin and α-viniferin [27–30].

The phytoalexin response in UV-treated commodities is modulated by the physiological status of the plant organ at the time of the treatment, as well as by storage duration. Wounded carrot roots were shown to accumulate higher levels of 6-MM in response to UV treatment than unwounded roots [31]. It was also observed that the physiological age of carrot root and tomato fruits affected the intensity of the phytoalexin response. Roots treated immediately after harvest (fresh roots) accumulated higher levels of 6-MM than older roots (stored for 4 months) [16]. Older carrot roots also required a higher dose to express the phytoalexin response. When treated at the mature-green stage, tomato fruits showed a greater ability to synthesise and accumulate rishitin than fruits at the turning stage [15]. A similar age effect was also reported for orange [32, 33]. Storage conditions, namely temperature and relative humidity (RH), had a significant impact on the phytoalexin response. Tomato fruits stored at 13ºC and 95% RH for 12 or 22 days had a higher rishitin content than fruits stored at 20ºC and 75% RH [15]. A higher level of 6-MM was found in carrot slices stored at 4°C than in those stored at 10ºC [18].

Varietal differences also exist in the ability to accumulate phytoalexins in response to UV. This was demonstrated with carrot roots in the accumulation of 6-MM [34]. Related species of a single family also vary in their capacity to accumulate the same phytoalexin in response to UV [33]. Significantly higher levels of scoparone accumulated in lemon, kumquat and orange, but accumulation was low in grapefruit and lime [19]. It was also observed that heat treatment combined with inoculation (*P. digitatum*) induced a higher level of the phytoalexin in these fruits than UV-C treatment alone

[19, 35]. Furthermore, the phytoalexin profile may be altered depending on the UV dose. In kumquat fruits treated with a low UV dose (0.3 kJ/m^2), scopoletin was the major phytoalexin, whereas at a higher dose of 1.5 kJ/m^2, scoparone was the main phytoalexin isolated from the fruit flavedo [36].

Defence mechanisms other than phytoalexin response have received little attention thus far, although the potential for the expression of other defence-related genes in postharvest commodities exists. A study by Porat *et al.* [37] presented evidence for the involvement of pathogenesis-related (PR) proteins, namely chitinase and β-1,3-glucanase, in the resistance of UV-irradiated grapefruit to *P. digitatum*. While UV treatment alone can cause chitinase expression, a combination of both wounding and UV treatment was necessary to trigger β-1,3-glucanases in grapefruit flavedo tissue [37]. Antifungal hydrolases, some of which are PR proteins, were reported in bell pepper [23], tomato [17, 20] and carrot roots [38] in response to UV treatment. In carrot roots, a chitinase was induced by UV-C application but also by infection with *B. cinerea* [38], a finding that confirms the PR status of this hydrolase. Both chitinases and β-1,3-glucanases were induced in tomato fruits by UV-C alone [17, 20]. Increased chitinase and β-1,3-glucanase activities were detected in peach fruit extracts as early as 6 h after UV treatment, reaching a maximum level at 96 h [39]. Enhancement of both chitinase and glucanase activities were also observed in UV-treated grape leaves [40].

UV irradiation is known to stimulate the phenylpropanoid pathway of all plant parts, as demonstrated by the activation of the key enzyme of this pathway, phenylalanine ammonia-lyase (PAL). PAL activity was enhanced in UV-treated grapefruit [9], sweet potato [41] and peach [39]. The metabolites from the phenylpropanoid pathway exert a protective role against pathogenic organisms through direct inhibition of growth, inactivation of fungal hydrolases or reinforcement of host cell walls. Elevated phenolic content was noticed in UV-treated strawberry [42] and tomato [20, 43], likely contributing to the inactivation of fungal hydrolases [44]. Histochemical and ultrastructural studies provide evidence of the possible involvement of phenolic compounds in resistance to *B. cinerea* [20]. Cell-wall-strengthening compounds (lignin and suberin) were involved in the observed resistance of UV-treated tomato fruits to *B. cinerea* [20]. The resistance of UV-treated grapefruit to *P. digitatum* was associated with enhanced activity of peroxidase, a key enzyme involved in lignin synthesis [9].

Maintenance and improvement of quality attributes

Control of senescence
The rate of metabolic activities in UV-C–treated tissue was modified following treatment as indicated by the change in the respiratory pattern reported for some postharvest com-

modities [12, 23, 43]. In tomato fruits a rapid and transient increase in CO_2 production immediately after irradiation was reported. Compared with the control, however, the overall CO_2 production was lower in the UV-treated fruits, and the CO_2 climacteric rise was delayed by 7 days. Ethylene (C_2H_4) synthesis followed a similar pattern. The delayed climacteric rise (CO_2 and C_2H_4) was interpreted as indicative of delayed senescence resulting from UV treatment. The transient rise in CO_2 and C_2H_4 observed in tomato following UV treatment was presumed to be an adaptation of the tissue to the oxidative stress caused by UV light. The data obtained by Maharaj *et al.* and Maharaj [12, 43] indicate that the stimulation of multifunctional antioxidants such as polyamines (namely putrescine, agmatine and tyramine) and phenolics (namely salicylic acid, vanillin, ferulic acid, 7-hydroxycoumarin and rutin) may account for the observed delay in senescence. Detoxification of active oxygen species may also play a role in retarding senescence [45].

Changes in firmness
Firmness is a very important quality factor for postharvest fruits and vegetables. Firmer produce are better able to withstand postharvest handling and transportation. Nevertheless, tissue softening is essential for most fruits towards the end of storage to impart desirable palatability. UV-C irradiation appears to slow down the softening rate of several fleshy fruits. Higher firmness indices were reported for UV-treated strawberry [23, 46], peach [47, 48], apple [48] and pepper [49]. Similar results were observed for UV-treated tomato fruits, which remained firmer over a longer period compared with the control [11–13, 44]. In UV-treated tomato, the activity of polygalacturonase, an enzyme associated with fruit softening during ripening, was lower than in the control [44]. The activity of other cell-wall-degrading enzymes was also found to be reduced in UV-treated tomato [50]. However, a sensory panel did not find a significant difference in texture between UV-treated tomato and the control at the end of the storage period [51].

Changes in taste and flavour attributes
The effect of UV-C treatment on attributes contributing to taste, such as free sugars assessed as total soluble solids and titratable acidity, have been studied in several UV-treated horticultural crops. Baka [23] found a higher level of free sugars in treated fruits than in controls; strawberry and bell pepper. In UV-treated peach [47, 48], apple [48], onion [52] and sweet potato [53, 54], however, the sugar content was lower, although in the case of onion, the difference was not significant [52]. Charles *et al.* [51] did not observe any significant difference in the evolution of total soluble solids in UV-treated tomato during storage, nor did Vicente *et al.* [49] in UV-treated pepper.

Titratable acidity was found to decrease at a slower rate in UV-treated strawberry and bell pepper [23], but UV-C did not significantly affect either the pH or the acidity of apple

[48]. While the latter study reported a similar pattern for the pH value of peach, the acidity was significantly higher in the treated fruits. An opposite trend in titratable acidity was noticed in UV-treated tomato fruits during 20 days of storage at 13ºC, although observed differences were not always statistically significant [51].

Phenolic compounds can contribute to the flavour of fruits. Maharaj [43] reported significant increases in phenolic compounds in UV-treated tomato fruits. However, a sensory panel found UV-treated tomato fruits to be comparable in taste to either control or store-bought fruits [51]. Similarly, UV-treated citrus fruits (kumquat and Washington navel orange) did not differ in taste from the control [55]. The accumulation of the isocoumarin 6-MM is associated with the development of a bitter taste in stored carrot roots exposed to ethylene [56]. Although a significant level of 6-MM was induced in carrot roots and slices in response to pre-storage UV-C treatment [16, 18], sensory evaluation of the cooked carrot roots showed no significant difference between the treated roots and the control [57]. It was shown that 6-MM leached out into the boiling water and that the peeling operation also reduced the 6-MM level in the cooked slices, since this compound accumulates mainly in the epidermic and exodermic tissues [57]. In addition, a sensory panel could not differentiate UV-treated onions from the control, both in the fresh and cooked forms [52].

Changes in colour and general appearance
The colour and general appearance (turgidity or shrivelling) of fresh stored fruits and vegetables can be a decisive factor in their acceptance or rejection by the consumer. During ripening, fruit colour change is due to chlorophyll loss, the unveiling of pre-existing carotenoids, and the synthesis of carotenoids such as lycopene and other pigments such as anthocyanins. From the standpoint of prolonging shelf-life, it is desirable that these changes take place at a slower rate. Several authors have described the delay in colour change induced by UV-C in treated fruits and vegetables [12, 13, 23, 43, 49]. In pepper and broccoli [23, 49, 58] and tomato [13, 43], UV-C irradiation significantly delayed chlorophyll loss. Concomitant with this delay, the evolution of lycopene was also slowed in tomato [12]. However, colour development was accentuated by UV treatment in strawberry fruits with a concomitant increase in anthocyanin accumulation [59].

Doses higher than the hormetic dose led to detrimental bronzing and duller appearance in tomato fruits [12, 13] and altered the appearance of citrus fruits [19]. Fruit surface scalding occurred in papaya at all UV doses applied [60]. At higher doses, yellow lemon fruits exhibited less damage than green fruits [19]. The negative effect of UV-C treatment on appearance could lead to rejection of this promising alternative, at least for some crops (eg, avena mandarins [61]). D'hallewin *et al.* [61] did not consider UV-C to be an effective method compared with either heat treatment or thiabendazole, mainly because of the poor visual appearance of the

UV-C-treated fruits, even though the level of decay control was significant (less than 50% of the control). The consumer usually judges food products as sound when they are free of any visual defects. This may raise the question of choice for the consumer between reduced chemical residues in food and a lower esthetic value of the UV-C-treated fruits or vegetables. It is possible that the extensive loss of sensory quality observed by D'hallewin *et al.* [61] might have been due to overexposure. Similar quality losses were also observed in other crops when doses were higher than the hormetic dose [8, 9, 12, 13, 19].

Weight loss in postharvest crops during storage may be attributed to loss of water through transpiration or to loss of substrates (sugar and organic acids) through respiration. Water loss may cause shrivelling of the stored commodity, with a serious effect on general appearance. In bell pepper [62], a combination of UV treatment and hot water dipping resulted in lower weight loss than in the control. A modest weight loss was also noted in UV-treated sweet potatoes [53], but weight loss was higher in UV-treated tomato fruits than in the untreated control, although not significant enough to cause shrivelling [12]. UV-C treatment caused severe shrivelling of kumquat when the produce was stored at 17ºC [19]. This deleterious effect, however, was reduced by storage at lower temperatures.

Changes in bioactive compounds
UV hormesis is seen as a technology that could also be used to enhance the beneficial health properties of fresh fruits and vegetables [2, 36, 63]. This hypothetical view is based on the ability of this abiotic elicitor to activate several paths leading to the synthesis and accumulation of secondary metabolites, some of which are well characterised for their positive impact on several aspects of human health. The most cited example is the elicitation of the stilbene resveratrol in table grape by UV treatment [63]. This molecule has been widely studied for its potential to protect against or alleviate the symptoms of several human ailments and diseases. The prophylactic and therapeutic actions of resveratrol have been described as anti-oxidant, cancer chemopreventive, anti-infection, antiviral, anti-inflammatory, anti-ischaemia, cardioprotective, neuro-protective, anti-aging and obesity-controlling [64]. UV treatment increased the level of resveratrol 10-fold in table grape skin compared with untreated fruit skin [63]. Besides table grape, numerous plants have been identified as resveratrol sources [64]. There is therefore a potential for the biosyn-thetic pathways leading to increased resveratrol accumulation to be activated by UV hormesis in other edible plant foods.

The bioactive coumarin scoparone, naturally isolated from the Chinese herb *Artemisia scoparia* [65], was induced in citrus fruits by UV hormesis [8, 9, 19, 33, 36, 61, 66], as well as by heat treatment [35]. Scoparone was shown to be an antiproliferative agent and a smooth muscle relaxant, and to reduce total serum cholesterol and triglycerides [67]. In a hyperlipidaemic diabetic rabbit model, scoparone was shown

to lower plasma cholesterol and slowed the development of atherosclerosis [65]. However, a preliminary study using a murine model was not conclusive with respect to the benefi-cial effect of scoparone-enhanced UV-treated kumquat fruits peel [36]. Animals that were fed freeze-dried peels with an alleged 30-fold increased level of scoparone did not show any hypolipidaemia compared with control animals fed non-UV-treated kumquat peels, presumably because of a reduc-tion in the total antioxidant levels in the peel of the UV-treated fruits [36].

Degenerative, chronic and age-related diseases all have an oxidative component [68], and increased consumption of foods with a high antioxidant potential is recommended for prevention of these diseases. Fresh fruits and vegetables are an integral part of a healthy diet due to their high antioxidant potential, often linked to their antioxidant vitamins, phenolic compounds and pigments. UV-C illumination of fresh straw-berry fruits was shown to cause a significant enhancement of the total antioxidant capacity [36, 42]. The increased antioxi-dant capacity of UV-treated strawberry was likely due to the elevated levels of phenolic compounds, although the titre of anthocyanin pigments was lower than in the control [42]. The results of Erkan [42] on the effect of UV on anthocyanins in strawberry contradict the results reported by Baka *et al.* [59]. In the latter study [59], higher anthocyanin content was noted in the treated berries at the end of the storage period. In other fruit systems, such as ready-to-eat pomegranate arils [69] and table grape [28], UV-C treatment did not cause any signifi-cant change in anthocyanin content.

At least one study reported a change in the carotenoid profile in UV-treated tomato [70]. Reductions in lycopene content in UV-treated tomato fruits [12, 13, 71] and in total carotenoids in pepper [49] were observed. The negative impact of UV-C treatment on carotenoids may be considered a drawback, particularly with regards to lycopene, which is highly valued as a phytochemical that is beneficial to human health. On the other hand, both histochemical [20] and chemical [43] analy-ses revealed higher phenolic content in UV-treated tomato. Similarly, UV-C treatment resulted in a significant increase in total phenolics in strawberry fruits [42]. The increase in phenolic compounds in UV-treated fruits may well compen-sate for the reduction in antioxidant pigments, resulting in a higher antioxidant capacity of UV-treated fruits as in straw-berry [42]. The antioxidant capacity was also higher in UV-treated pepper [49].

Future directions for the application of UV treatment
The body of evidence available on the beneficial impact of UV hormesis on horticultural produce suggests that the tech-nology could be seriously considered for commercialisation [14, 72]. To our knowledge, however, only one study has addressed an online apparatus with possible commercial de-velopment [73]. Most of the studies on the effect of UV-C light on horticultural produce have been carried out with

laboratory-scale devices using low-pressure mercury lamps with maximum peak emission at 254 nm. Designing a system to deliver hormetic UV doses must account for the fact that the induction process seems to be non-systemic [38] and, therefore, the entire fruit must be uniformly exposed to UV light. This may not be true for all commodities, given that it was recently shown that exposing the stem end of apple, peach and tangerine to UV-C provided protection comparable to that obtained by rotating the fruit to expose all four quarters [74]. Another aspect of UV treatment that should be considered is the range of factors that can affect the hormesis responses. The research papers surveyed in the present report demonstrate that UV response is dependent on produce type, cultivar, maturity stage, physiological age, harvest season and targeted pathogen, as well as other factors that have yet to be defined. Information on the potential impact of post-treatment handling conditions on the expression of UV hormesis is lacking. Evidently, the task at hand could be perceived as a very challenging one, since all the factors that negatively impact the expression of the desired beneficial responses must be overcome by an effective technological design. There is ample evidence to suggest that UV hormesis cannot be advocated as the *panacea* for every postharvest system, but it does present opportunities for some, and hence there is scope for developing procedures and equipment for the application of this new technology. It is also clear that multidisciplinary research involving postharvest physiology, plant pathology and engineering will be needed for successful implementation.

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