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Ultraviolet Light Stimulates Flavonol Accumulation in Peeled Onions and Controls Microorganisms on Their Surface

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The effects of ultraviolet (UV) light on flavonol content in peeled onions (*Allium cepa* L.) and on microbial survival on their surface were investigated. The content of phenolic compounds showed a gradient within the onion bulb, with the highest level in the external dry "skin" (tunic) and the lowest level in the center. Peeled bulbs were treated with UV light comprising the bands of UV-C (more than half of the total UV output), UV-A, and UV-B. The response to UV depended upon the position of the scales within the bulb. In the outer fleshy scales, the UV doses of 1.2−6 kJ m^{-2} approximately doubled the accumulation of flavonols and the total antioxidant capacity. When mid-depth (5th from the outside) scales were exposed to UV, the lowest dose tested (1.2 kJ m^{-2}) had no significant effect on flavonols accumulation, whereas the higher doses decreased their levels. The low-dose UV treatment reduced the count of *Escherichia coli* on artificially contaminated peeled onions by 1.5−3 logs and alleviated the decay of *Penicillium*-inoculated bulbs. The present study has demonstrated a potential of UV light for simultaneous decontamination of peeled onions and their enrichment in health-enhancing phytonutrients.

KEYWORDS: Bulb onion; *Allium cepa* L.; scales; fresh cut; flavonoids; quercetin; spiraeoside; kaempferol; UV; decontamination; *Penicillium* sp.; *Escherichia coli*

INTRODUCTION

Postharvest physiological stimulation is one of the possible approaches to enrichment of fruits and vegetables in phytonutrients. The approach is based on the idea that application of controlled postharvest stresses can elicit production of defensive constituents in plant organs and that many of these constituents are beneficial to human health (*1*). Electromagnetic radiation in the visible and/or ultraviolet (UV) ranges is one of the factors that can stimulate the production of phytonutrients in harvested fresh produce (*2*,*3*). This approach is especially efficient for production of phenolic substances, e.g., flavonoids known as plant photoprotective constituents. UV illumination was reported to increase phytonutrient levels and antioxidant capacity in several commodities (*3*).

Allium vegetables, such as bulb onion (*A. cepa* L.), green onion (*A. fistulosum* L.), garlic (*A. sativum* L.), leek (*A. ampeloprasum* var. *porrum* L.), and chives (*A. schoenoprasum* L.) have undisputable reputations as healthy foods (*4*). The important bioactive constituents of onions include flavonoids (primarily derivatives of the flavonols quercetin and/or kaempferol), phenolic acids, and organosulfur compounds. In *A. cepa*, the major flavonoids are quercetin 4′-glucoside (spiraeoside) and quercetin 3,4′-diglucoside. Other flavonol glycosides and free aglycones are present in smaller amounts. In addition, red onion varieties contain anthocyanins, mainly cyanidin derivatives (*5*).

Information about photostimulation of biosynthesis of phenolics in *Allium* vegetables is limited. The possibility of enhancing the quercetin level in onion slices with UV light was briefly reported by Higashio et al. (*6*), who observed that lamps emitting predominantly short-wave (UV-C, 254 nm), medium-wave (UV-B, 310 nm), and long-wave (UV-A, 352 nm) UV light all induced similar, moderate effects. However, to achieve substantial (50−75%) increases in quercetin content demanded long-duration UV-A exposures of 12 or even 24 h. Increased quercetin levels in whole or diced onions were also elicited by γ irradiation (*7*). At the preharvest stage, growing under supplementary UV-B irradiation increased flavonol content in chives (*8*). In addition, an effect of sunlight was found to be involved in quercetin buildup in onions during field curing, a practice that involves leaving bulbs in the field for about 10 days after lifting (*9*).

Although onion is known for its antimicrobial properties, it still encounters postharvest microbiological problems of two kinds: spoilage caused by phytopathogenic organisms and risk of carrying foodborne diseases because of survival of human pathogens on the produce. *Penicillium allii* is a fungal causative agent of postharvest blue mold rot of onions (*10*). Fresh-cut (peeled, sliced, or diced) onions are of special concern from the food safety point of view, because of the high microbial load on the raw material (*11*). Pathogenic *Escherichia coli* O157:H7 survived on onions growing in artificially contaminated soil for at least 1.5 months, although the bacterial count on the produce gradually declined (*12*). The antimicrobial potency of onion was insufficient to kill *E. coli* (*13*). Novel decontamination agents for fresh-cut onions are being sought. In particular, a combination of ultraviolet illumination with hydrogen peroxide showed promising results for inactivation of human pathogens and spoilage bacteria on the surface and within onion slices (*14*).

In the present study, we tried to simultaneously exploit the eliciting and antimicrobial potentials of the ultraviolet light.

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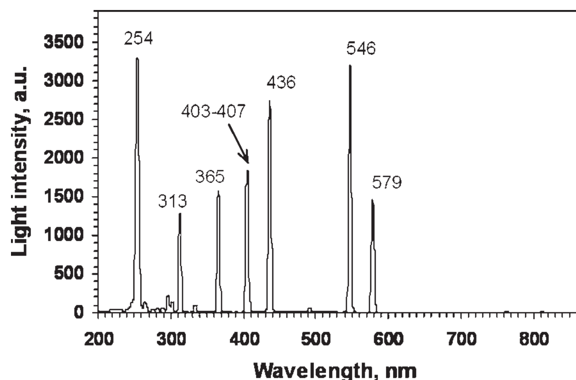

Figure 1. Emission spectrum of the UV illumination chamber. The major bands were 254 nm, UV-C; 313 nm, UV-B; 365 nm, UV-A; and above 400 nm, visible light.

Our aim was to check the influence of UV exposure on flavonol content in peeled onions and on survival of microorganisms on their surface.

MATERIALS AND METHODS

Chemicals. All reagents except those specified below were purchased from Sigma (St. Louis, MO). Spiraeoside (quercetin 4′-glucoside) was purchased from Carl Roth GmbH (Karlsruhe, Germany), and kaempferol was purchased from Extrasynthese (Genay, France). Orthophosphoric acid was from BDH Chemicals (Poole, England), and high-performance liquid chromatography (HPLC)-grade methanol was from Labscan (Dublin, Ireland). The other solvents were supplied by Gadot (Netanya, Israel). Deionized water was prepared with the Nanopure system (Barnstead, Dubuque, IA).

Plant Material and Sample Preparation. Brown onions (cv. Orlando) were obtained directly from the grower (Kfar Hasidim, Israel). According to the local agricultural practice, the commercial lifting was conducted at a stage of 50% fallen leaves, similar to the practice described by Mogren et al. (*15*), but the onions did not undergo field curing. The onions were stored at 1 °C at the Department of Postharvest Science, Agricultural Research Organization (ARO), The Volcani Center.

The trials were conducted with undamaged bulbs of regular shape that had been kept in cold storage for 1.5−3 months. After transfer from the storage room, the bulbs were kept at 20 °C for 3 h, for temperature equilibration. For initial illumination trials, the bulbs were peeled by either (a) removal of the external inedible "skin" (tunic), to expose the outer (1st from the outside) edible fleshy scale or (b) removal of the tunic and 4 outer fleshy scales, to expose the middle (5th from the outside) fleshy scale. In both cases, the bulbs were trimmed at top and bottom to remove the roots and the tunic residue. In other trials, the bulbs were peeled as in case above and wrapped in aluminum foil with an opening ("window") of 20 mm in diameter. This approach enabled a comparison of phytonutrient contents on irradiated and non-irradiated sides of the same bulb.

Treatment. The bulbs were treated in a chamber fitted with four G15T8 germicidal low-pressure mercury-arc lamps (General Electric, Fairfield, CO). The emission spectrum of the device measured with the USB2000 spectrometer (Ocean Optics, Dunedin, FL) is presented in **Figure 1**. As is typical of mercury lamps, short-wave UV (UV-C) accounted for more than half of the total UV emission, and the rest was distributed almost equally between the medium-wavelength UV-B and long-wavelength UV-A bands. Therefore, in the present paper, we have not specified which ultraviolet range (A, B, or C) was used, because all three ranges were represented in the emission spectrum. In addition, the lamps emitted visible light.

The bulbs were placed on their sides inside the irradiation chamber at a distance of 26 cm from the lamps, where the total UV flow, as measured with a UVX radiometer (UV Products, Inc., San Gabriel, CA), was 18 W m^{-2}. Thus, the bulbs received a radiation dose of 1.2 kJ m^{-2} in about 67 s. Desired UV doses were obtained by varying the exposure duration. In initial trials, the bulbs were treated twice, first laying on one side and then on the opposite one, to ensure uniform irradiation of the whole surface. In the trials with aluminum foil wrapping, the "window" in the foil faced the lamps. After the treatment, the foil was removed and the bulbs were stored in perforated polyethylene bags, at 17 °C in the dark.

Sampling and Extraction. The bulbs were sampled 0, 2, 4, or 5 days after treatment, as specified below. Discs were excised from irradiated and non-irradiated scales with a cork borer, weighed, immediately dipped into liquid nitrogen, and freeze-dried in a model FD5508 freeze dryer (ilShin Lab Co., Yangju, Gyeonggi, South Korea). The freeze-dried samples were kept at −20 °C pending extraction.

For extraction, the freeze-dried material was ground to a fine powder. Samples of 0.1 g of dry matter were extracted with 80% ethanol. For hydrolysis of flavonol glycosides, 1 mL of the ethanolic extract was mixed with 1 mL of 4 N HCl, incubated on a water bath at 80 °C for 30 min, and then cooled to room temperature.

Spectrophotometric Analyses. The total content of phenolic compounds was determined with a Folin−Ciocalteu assay according to Singleton and Rossi (*16*), using gallic acid as a standard.

Flavonols were quantified spectrophotometrically according to Lombard et al. (*17*) as absorbance at 362 nm using a Ultrospec 2100 Pro spectrophotometer (Biochrome, Cambridge, U.K.). Although this assay originally was presented as a method for quercetin measurement, we interpreted the results as total flavonol content, because all flavonols absorb at this wavelength. The results for non-hydrolyzed samples were expressed as the concentration of spiraeoside, and those for hydrolyzed samples were expressed as the concentration of quercetin, by means of appropriate calibration curves.

HPLC Analysis. The Shimadzu HPLC system included a LC-10AT pump with a SPD-M10AVP photodiode array detector and a Sil 10AD VP autosampler (Shimadzu, Kyoto, Japan). The system was equipped with an ODS Hypersil C18 5 μm, 250 × 4.6 mm column (Thermo Electron Corp., Waltham, MA) and operated in the isocratic regime with a mobile phase comprising methanol, water, and orthophosphoric acid in proportions of 55:45:0.2. The authentic compounds were used as external standards.

Antioxidant Capacity Determination. Hydrophilic and lipophilic antioxidant fractions were extracted, and their activities were determined with the Trolox equivalent antioxidant capacity (TEAC) method in a version by Vinokur and Rodov (*18*).

Microbiological Trials. A colony of *E. coli* American Type Culture Collection (ATCC) 25922 grown overnight on a nutrient agar medium (Difco Laboratories, Troy, MI) was suspended in 2 mL of sterile deionized water containing 0.01% Tween 80. The optical density of the suspension was measured at a wavelength of 550 nm, and the suspension was diluted on the basis of preliminary data to reach the bacterial count of about 10^6 colony-forming units (CFU) mL^{-1}. Peeled, unwounded onions were inoculated by spreading a drop (40 μL) of the bacterial suspension on a marked area of approximately 4 cm^2 in the equatorial region of a bulb; 20 bulbs were inoculated. Half of the inoculated bulbs were kept under air flow in the laminar hood until the bacterial droplets dried; the others were kept in a plastic tray without air flow, so that their surface stayed wet for approximately 1 h. The UV treatment at a dose of 1.2 kJ m^{-2} was applied on either dried or wet inoculated surfaces, and untreated inoculated bulbs served as controls. Bacteria were recovered from the bulb surface 3 h after inoculation by gentle resuspending in 40 μL of sterile water; 10 μL aliquots of the suspension were plated on Chromocult TBX agar (Merck, Darmstadt, Germany), 3 plates from each inoculation site. The number of surviving *E. coli* CFUs was determined after incubation at 44 °C for 18−24 h, as recommended by the medium manufacturer.

Phytopathological Trials. A culture of *Penicillium* sp. previously isolated from a blue-mold-infected peeled onion was grown on a potato dextrose agar (PDA) medium supplemented with chloramphenicol (100 mg L^{-1}) for 4 days at 25 °C. The culture was provisionally identified as *P. allii*, in accordance with Overy et al. (*10*). Spores were washed from the culture surface with 5 mL of sterile deionized water containing 0.01% Tween 80 and filtered through a double layer of cotton gauze. The spores were counted with a hemocytometer (Spencer Bright-Line, Fisher, NJ), and the suspension density was adjusted to 5×10^4 spores mL^{-1}. The bulbs were superficially wounded by pressing a 1 cm^2 piece of medium-coarse sandpaper against the surface of the peeled onion and were inoculated by applying 10 μL of the spore suspension to the wound. Within 3 h after the inoculation, the bulbs were either subjected to the UV treatment at doses of 1.2 or 3.6 kJ m^{-2} or left untreated to serve as a control. Each treatment group included three replications, each of 10 bulbs. The inoculated bulbs

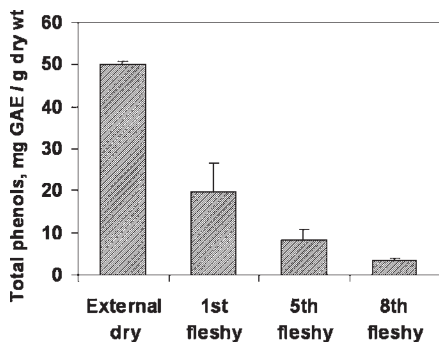

Figure 2. Total content of phenolic compounds in different parts of an onion bulb, cv. Orlando. The fleshy scales are counted from outside: 1st, outer; 5th, mid-level; 8th, inner. The error bars represent 95% *t* confidence intervals.

were kept in the cavities of plastic insert trays, one bulb per cavity, and stored for 5 days at 20 °C under saturated humidity conditions.

Disease development was evaluated at the end of the storage period according to visual signs of decay, i.e., tissue maceration and/or characteristic sporulation, and expressed as a percentage of healthy (asymptomatic) bulbs out of the total number of inoculated bulbs in the replication and as a disease index (DI), which was calculated as follows:

$$DI = [(0H) + (1M) + (2S)]/N$$

where H is the number of healthy bulbs, M is the number of bulbs with macerated lesions without sporulation, S is the number of bulbs with sporulation, and N is the total number of bulbs in the replication.

Statistics. The experiments were performed at least in triplicate. The Microsoft Office Excel spreadsheet was used to calculate means, standard deviations, and 95% t confidence intervals. Means were separated by application of Tukey's 5% "honestly significant difference" (HSD) test following one-way analysis of variance (ANOVA) by means of SAS Software, version 8.01 (SAS Institute, Cary, NC). Flavonol content in irradiated and unirradiated sides of the bulbs were compared by means of the paired Student's t test.

RESULTS

Phytonutrient Content. The concentrations of phenolic compounds in whole (unpeeled) onion bulbs decreased from the periphery toward the center, with the highest content in the tunic and the lowest content in the internal tissues. The phenolic content in the outermost edible fleshy scale was approximately twice that in the 5th scale inward (**Figure 2**). These two bulb parts were selected for illumination trials to check if their difference in phenolic content could be negated by UV exposure.

At 2 days after the illumination, the UV-treated outer scales contained significantly more flavonols than the untreated control (**Figure 3A**). At this stage, no difference was observed between the effects of the three UV doses. However, whereas the flavonol content continued to increase until day 4 in the samples treated with low and medium UV doses (1.2 and 6 kJ m^{-2}), in the bulbs treated with the high dose (12 kJ m^{-2}) accumulation stopped on day 2. It should be noted that the flavonol content in the outer fleshy scales varied widely between individual bulbs, as illustrated by the relatively high HSD value (panels **A** and **B** of **Figure 3**).

Similar to the total phenolic content, the concentration of flavonols in the mid-depth scales was approximately half that in the outer ones. Furthermore, these scales differed in their responses to the UV light. The flavonol content in the mid-depth scales that had been exposed to medium and high UV doses significantly declined, and only those in scales treated with the low dose (1.2 kJ m^{-2}) increased slightly, although not significantly more than those in the untreated control (**Figure 3B**).

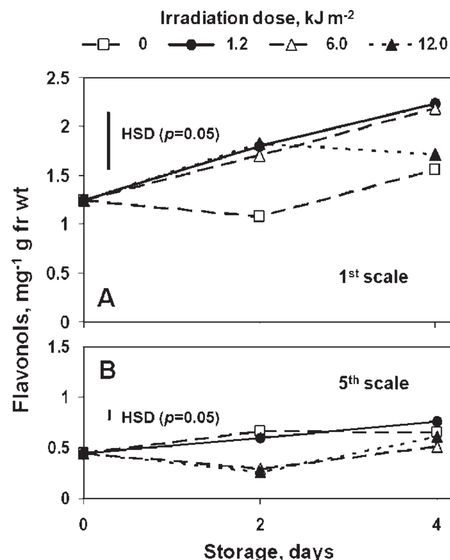

Figure 3. Effect of exposure to various doses of UV on the content of flavonols in the (A) outer and (B) mid-level fleshy edible scales of onion, cv. Orlando. The bars represent the 5% Tukey's HSD values.

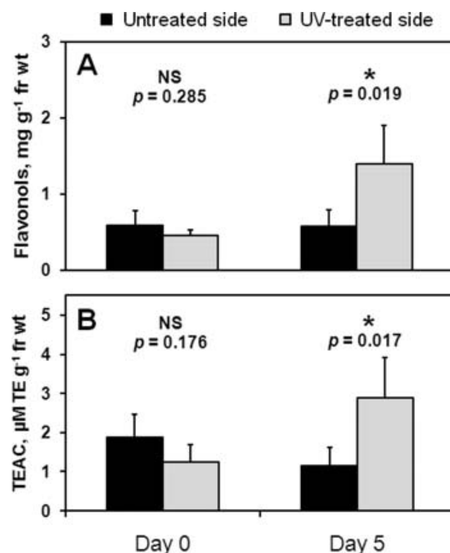

Figure 4. (A) Content of flavonols and (B) TEAC in outer edible scales on untreated and UV-illuminated sides of peeled onion bulbs immediately after treatment ("day 0") and after 5 days of storage ("day 5"). The UV dose was 2.4 kJ m^{-2}. The marks represent the difference between the unilluminated and illuminated sides, whose significance was determined by paired Student's t test: NS, non-significant; $*$, significant at the p value indicated below. The error bars represent the 95% t confidence intervals.

To reduce the effect of interbulb variability, a further comparison was made between the irradiated and unirradiated sides of individual bulbs, as described in the Materials and Methods. **Figure 4** shows that, before the treatment, the flavonol contents on the opposite sides of a bulb were similar, whereas 5 days after exposure to UV at 2.4 kJ m^{-2}, the treated side accumulated significantly more flavonols. This rise in flavonol content was paralleled by a concomitant increase in hydrophilic antioxidant capacity (**Figure 4**). The activity of lipophilic antioxidants in the fleshy onion scales was negligible (data not shown).

Similar to its effect on total flavonols, UV treatment significantly enhanced the levels of individual compounds, such as free and sugar-bound quercetin and kaempferol (**Table 1**). Whereas the

Table 1. Effect of Ultraviolet Irradiation on the Content of Major Flavonoid Compounds in External Fleshy Scales of Onion (cv. Orlando)[a]

compound (μg g^{-1} fresh weight)	untreated	UV treated
Without Hydrolysis		
quercetin	5.0 ± 2.4	19.4 ± 8.8
kaempferol	8.8 ± 4.2	45.7 ± 29.6
spiraeoside (quercetin-4′-glucoside)	219.5 ± 63.2	542.9 ± 233.2
After Hydrolysis		
quercetin	385.5 ± 162.0	1132.3 ± 539.2
kaempferol	25.7 ± 9.0	73.8 ± 29.0

[a] The data presented are means of three replications ± 95% *t* confidence intervals.

amount of spiraeoside in the irradiated bulbs increased approximately 2.5-fold as compared to that in the untreated control, the free aglycone contents increased 4−5-fold. Quercetin glycosides, other than spiraeoside, were not quantified because of the lack of standards. However, the comparison between the amount of quercetin released after the hydrolysis and the initial spiraeoside content showed that these glucosides (primarily quercetin 3,4′-diglucoside) accounted for approximately half of the total bound quercetin, and their accumulation was enhanced by UV similar to spiraeoside. In contrast to quercetin, hydrolysis resulted in only a moderate increase in kaempferol content, which indicated that the latter compound was present in the bulbs predominantly in the free form. Besides flavonoids, HPLC analysis revealed the presence of phenolic acids, e.g., gallic and protocatechuic acids, in the extracts. The acid contents were not significantly affected by the UV treatment (data not shown).

Antimicrobial UV Effects. Exposure of *Penicillium*-inoculated bulbs to UV light alleviated the disease but did not completely prevent it. At 5 days after the inoculations, more than 90% of untreated bulbs showed advanced decay, with sporulating pathogen on the wound surface. At the same time, about 30% of the inoculated bulbs that had been treated with the low UV dose remained healthy (**Figure 5A**). In addition, the UV treatment inhibited pathogen sporulation on the surface of infected bulbs (**Figure 5B**).

Recovery of *E. coli* from the surface of inoculated untreated bulbs was about 3 log CFU cm^{-2}, irrespective of the drying procedure. When UV was applied to inoculated bulb surfaces after drying, *E. coli* survival decreased to 1.5 log CFU cm^{-2}. No culturable *E. coli* cells were recovered following illumination of wet bulb surfaces.

DISCUSSION

The present study has demonstrated for the first time a potential capability of UV light to simultaneously decontaminate peeled onions and enrich them in human health-enhancing phytonutrients. Moreover, in contrast to the findings of Higashio et al. (*6*), our study has found that brief (1−2 min) UV exposure was sufficient to stimulate phytonutrient production and, at the same time, to exhibit antimicrobial effects of inhibiting spoilage and reducing bacterial load on the produce. However, it was also shown that the UV response depended upon the irradiation dose and tissue sensitivity, so that overexposure could result in flavonoid depletion.

Presumably, UV stimulation of flavonoid biosynthesis has photoprotective importance to the plant and could be interpreted as a case of hormesis, i.e., induction of a beneficial stress response by a low dose of a potentially harmful agent (*3*, *19*). However, this capability was fully realized only in the outer edible scales that

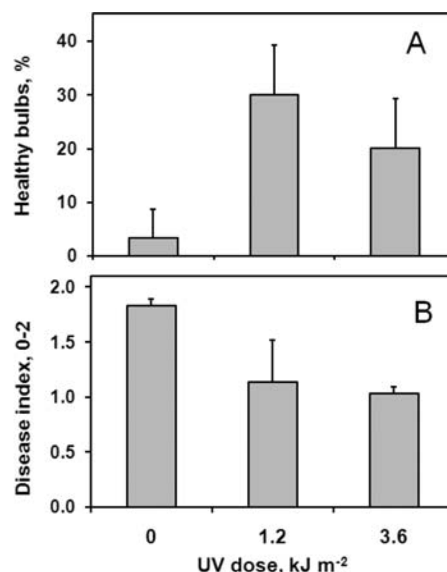

Figure 5. Effect of UV illumination on disease development in *Penicillium*-inoculated peeled onion bulbs after storage for 5 days at 20 °C and saturated humidity, expressed as (A) a percentage of asymptomatic bulbs and (B) disease index. The error bars represent the 95% *t* confidence intervals.

were initially relatively rich in flavonoids. The mid-level scales contained less phenolic compounds, in agreement with the gradient found in earlier studies (*20*). Contrary to expectations, after UV exposure, the accumulation of flavonols in the mid-level scales did not rise to that in the outer ones. Moreover, medium or high UV doses even further reduced the content of flavonoids. One may suppose that the irradiation doses that were stimulatory (hormetic) for the outer scales appeared injurious for the less protected middle ones. In fact, at the highest UV dose, signs of an inverse response were evident in the outer scales as well. Similarly, Higashio et al. (*6*) found that placing the onion slices too close to UV lamps negated the quercetin stimulation, supposedly because of a damaging effect of UV overdose.

The dependence of UV response on various internal and external factors may cause similar systems to yield apparently contradictory results. For example, Erkan et al. (*21*) observed increased contents of total phenolic compounds in UV-C-treated strawberries, whereas Allende et al. (*22*) obtained contrary results by applying a similar UV dose to a different strawberry cultivar. In our previous study with strawberries, cv. Tamar, UV doses of 1.5 and 4.5 kJ m^{-2} caused a transient increase in total antioxidant capacity if the irradiated fruits were subsequently stored at 5 °C, whereas storage at 10 °C caused the same doses to be inhibitory. The lowest dose of 0.5 kJ m^{-2} had no measurable effect on the antioxidant capacity at either temperature (*2*).

Adaptation of plant tissues to oxidative stress most likely underlies the phenomena observed. The oxidative cell status was shown to be a central element in a signal for induction of flavonoid biosynthesis in UV-challenged plant tissues (*23*). Barka et al. (*24*) observed a two-phase response of tomato fruits to postharvest UV-C treatment; signs of oxidative damage were evident at the first stage, but subsequent peroxidation markers in the UV-treated tomatoes became even lower than in the control unchallenged fruits, suggesting induction of a defense and/or repair mechanism. Similarly, increased antioxidant capacity was observed in our present study. However, excessive UV doses may cause irreversible damage to plants that results in depletion of antioxidative systems, which can be alleviated by exogenous antioxidants (*25*).

The differential response of onion scales to UV should be taken into account when it is considered as a possible treatment for fresh-cut products, such as diced onions or onion rings. According to our estimation, the outer fleshy scales may account for up to 30% (by weight) of fresh-cut onion products. Therefore, a treatment that doubled the phytonutrient content in the outer scales and had no negative effect on the others would result in a substantial 30% addition to the nutritional value. According to our present results, the low UV dose of 1.2 kJ m^{-2} could supply these benefits and, at the same time, exhibit a noticeable antimicrobial effect.

Wide variability in the quercetin content and UV responsiveness in onion bulbs from the same batch was observed in this study. A possible explanation of this phenomenon was found in the work by Mogren et al. (*9*), who demonstrated that quercetin accumulated in onions predominantly during the last week before lifting and that its level was strongly affected by the physiological age of the bulb at harvest. The quercetin content in mature bulbs with fallen leaves was almost twice that in physiologically younger bulbs with leaves still erect, but this difference was largely eliminated by subsequent field curing (*15*). However, because field curing is not practiced in Israel as a result of the local environmental conditions, the onion batch harvested at the stage of 50% fallen leaves might comprise two morphologically indistinguishable sub-populations that differed in quercetin levels and also possibly responsiveness to UV. The UV effect on onion taste and pungency was not examined in this work. However, we expect this effect to be insignificant as a result of the low penetrating capacity of the UV, because the flavor-related sulfur compounds, in contrast to flavonoids, are predominantly located in onions in the inner part of the bulb (*26*).

The efficacy of UV irradiation in reducing postharvest losses of horticultural crops has been demonstrated in numerous studies, summarized in the broad reviews by Stevens et al. (*19*) and Charles and Arul (*3*). Interestingly, this research direction was initiated in the 1980s with the work on whole, i.e., unpeeled, "Walla-Walla" onions (*19*). The control of postharvest diseases by UV treatments may involve two phenomena: a direct germicidal effect on the pathogen and indirect hormetic reactions that enhance the host disease resistance. We suppose that the disease alleviation observed in our present study was at least partially due to the direct germicidal action of the UV, because the onions were treated post-inoculation. A total of 1−2 days are typically needed for development of the UV-induced resistance mechanisms (*27*). In the absence of an instantaneous direct antimicrobial effect, this time could be sufficient for the pathogen to irreversibly colonize the wounds. On the other hand, the higher efficacy of the low UV dose than that of the medium dose in decay prevention (**Figure 5**) is typical of hormetic reactions.

The decreased *E. coli* count on the surface of inoculated peeled onions after the UV exposure was obviously a result of a direct germicidal effect, similar to that observed on fresh-cut pears (*28*). The germicidal activity played a significant role in the reduction of microbial load on minimally processed products by UV-C (*29*,*30*), although the involvement of indirect mechanisms, i.e., formation of phytoalexin-like antimicrobial compounds in fresh-cut melons, was reported by Lamikanra et al. (*31*).

Prospects for commercialization of UV treatments of fruits and vegetables are under consideration (*3*). Fresh-cut onion products might represent one of the potential items that could benefit by use of this approach to simultaneously improve both nutritional quality and microbiological safety. However, further optimization is still needed to achieve the best results with this technique.

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