Efficacy of Pulsed UV-Light for the Decontamination of *Escherichia coli* O157:H7 and *Salmonella* spp. on Raspberries and Strawberries

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ABSTRACT: Small fruits are increasingly being implicated in outbreaks of foodborne illness, and fresh produce is now the 2nd leading cause of foodborne illness in the United States. Conventional methods of decontamination are not effective, and there is a need to evaluate novel technologies. Pulsed ultraviolet (UV)-light is one such technology. In this study, pulsed UV-light was applied to strawberries and raspberries at varying UV doses and times. On raspberries, maximum reductions of *Escherichia coli* O157:H7 and *Salmonella* were 3.9 and 3.4 $\log_{10}$ CFU/g at 72 and 59.2 J/cm^2, respectively. On the surfaces of strawberries, maximum reductions were 2.1 and 2.8 $\log_{10}$ CFU/g at 25.7 and 34.2 J/cm^2, respectively. There was no observable damage to the fruits at these UV doses. The results obtained in this study indicate that pulsed UV-light has the potential to be used as a decontamination method for raspberries and strawberries.

Keywords: novel processing, pathogens, ultraviolet

Introduction

Each year, foodborne illnesses cost the U.S. economy $6.9 billion of loss in productivity and medical expenses (ERS 2005). Fresh produce has been increasingly implicated as the vehicle of transmission and is now the 2nd leading cause of foodborne illnesses, with 639 outbreaks during 1990 to 2004 (CSPI 2006). An estimated 73000 cases of *E. coli* O157 infections (Frenzen and others 2005) and 2000000 salmonellosis infections are reported each year in the United States (Frenzen and others 1999).

With increasing numbers of outbreaks tied to fresh foods, there is a need to evaluate novel processing technologies that do not destroy the integrity of the product: pulsed ultraviolet (UV)-light is one such technology. Pulsed UV-light, also referred to as pulsed light, broad-spectrum white light, high intensity light, or pulsed white light, utilizes electromagnetic radiation from 100 to 1100 nm (Green and others 2003). Pulsed UV-light is produced by storing electrical energy in a capacitor and releasing it in short bursts, which magnifies the power. These short pulses are believed to make pulsed UV-light a more efficient and effective method of application compared to conventional or continuous UV-light (Miller and others 1999). It has been reported that an equivalent level of inactivation can be achieved with pulsed UV-light up to 6 times faster than conventional UV-light (Fine and Gervais 2005). As with conventional UV-light, the predominant inactivation mechanism is through the formation of thymine dimers within the cells DNA (photochemical), which prevents the cell from replicating (Rowan and others 1999). However, with pulsed UV-light, additional modes of inactivation have been proposed: photothermal and photophysical (Krishnamurthy and others 2007).

The efficacy of pulsed UV-light has been well documented for inactivating foodborne microorganisms in suspension as well as in/on food. Rowan and others (1999) investigated the effects of pulsed UV-light on food-related microorganisms. Populations of *Listeria monocytogenes*, *E. coli*, *Salmonella* Enteritidis, *Pseudomonas aeruginosa*, *Bacillus cereus*, and *Staphylococcus aureus* that were seeded on tryptone soya–yeast agar media were exposed to pulsed light having either high or low content UV-light. Reductions between 2 and 6 $\log_{10}$ CFU/mL were attained using 200 pulses with low UV content and high content, respectively. Krishnamurthy and others (2004) investigated the use of pulsed UV-light to inactivate *S. aureus* in buffer solution and on agar seeded plates. They found a 7 to 8 $\log_{10}$ CFU/mL reduction of *S. aureus* on seeded agar plates and buffer solution at treatment times less than 5 s without significant temperature increase. Sharma and Demirci (2003) exposed alfalfa seeds inoculated with *E. coli* O157:H7 to pulsed UV-light. They found that when a seed layer of 1.02-mm thickness was treated for 30 s, a 4.80 $\log_{10}$ CFU/g reduction was achieved.

Small fruits such as raspberries and strawberries have been implicated in several notable outbreaks. Raspberries have been implicated in at least 5 outbreaks of *Cyclospora cayetanensis* (CDC 1997b), and strawberries have been implicated in 3 outbreaks of hepatitis A (CDC 1997a). While there have been no recorded bacterial outbreaks associated with small fruits, the possibility exists, since the contamination routes responsible for previous outbreaks are the same for bacterial pathogens. A U.S. Food and Drug Administration (FDA) survey found that 1 out of 143 imported strawberry samples tested positive for *Salmonella* (FDA 1999). Also, research has shown that both *Salmonella* and *E. coli* O157:H7 are capable of surviving on fresh strawberries for over 7 d (Knudsen and others 2001).

Throughout the production of small fruits, the opportunity for contamination exists due to improper sanitation, infected pickers, contaminated irrigation water, and manure fertilized fields (Han and others 2004). In spite of these risks, small fruits are not washed prior to delivery to market, due to the negative effect on fruit quality and shelf life. However, washing alone has been shown to have limited efficacy at removing both spoilage and pathogenic

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bacteria from the surfaces of produce, and conventional sanitizers have also shown limited efficacy (Yu and others 2001; Han and others 2004; Yuk and others 2006). Yu and others (2001) compared 5 sanitizers for the purpose of reducing populations of *E. coli* O157:H7 on strawberries. Of these 5 sanitizers, the most effective was found to be hydrogen peroxide, which gave a reduction of 2.2 $\log_{10}$ CFU/g.

The use of UV-C light for the purpose of extending the shelf life of berries has been well documented. Boysenberries treated with 0.92 J/cm^2 exhibited drupelet damage and texture, which was equivalent to a 45 °C heat treatment for 1 h. They also noted, compared to untreated, that treated berries had reduced softening during storage, lower respiration rates, and decreased anthocyanin leakage (Vicente and others 2004). Baka and others (1999) observed similar benefits of UV-C light treatment on strawberries. Strawberries treated with 0.1 J/cm^2 had a 5-d longer storage life, lower respiration rates, firmer texture, and increased anthocyanin content compared to untreated fruits. It has also been shown that exposure to UV-C light increases the resistance of a fruit to pathogens via the hormetic effect. It is believed that this effect may stimulate the production of certain compounds that can aid in the formation of phenolic compounds (Guerrero-Beltran and Barbosa-Canovas 2004). Based on the history of small fruit-associated foodborne illness outbreaks, the low efficacy of chemical sanitizers, and the potential bactericidal as well as quality benefits, the evaluation of pulsed UV-light for the purpose of decontaminating raspberries and strawberries was undertaken in this study.

Materials and Methods

Preparation of inoculum

Five strains of nalidixic acid resistant *E. coli* O157:H7 and *Salmonella* were obtained from the Center for Food Safety at the Univ. of Georgia. The *E. coli* O157:H7 strains were 932 (human isolate), 994 (salami isolate), E0018 (calf fecal isolate), H1730 (human isolate from outbreak associated with lettuce), and F4546 (human isolate from outbreak associated with alfalfa sprouts). The *Salmonella* serotypes used were Agona (human isolate from outbreak associated with alfalfa sprouts), Baildon (human isolate from outbreak associated with diced tomatoes), Gaminara (orange juice isolate), Michigan (human isolate associated with cantaloupe outbreak), and Montevideo (human isolate associated with tomato outbreak). Cultures were grown in tryptic soy broth (Difco, Detroit, Mich., U.S.A.) supplemented with 50 μg/mL nalidixic acid (TSBN) (Fisher Scientific Co., Fair Lawn, N.J., U.S.A.) at 37 °C for 24 h. A mixture of *E. coli* O157:H7 or *Salmonella* strains was prepared by combining 10 mL of each culture and centrifuging for 15 min at 3300 $\times$ *g* and 4 °C. The supernatant was discarded and the cells were resuspended in 10 mL of 0.1% peptone water (Difco) to yield an approximate population of 10^8 CFU/mL.

Inoculation of small fruits

Fresh red raspberries and strawberries were purchased from a local grocery store and left at room temperature for 1 h prior to inoculation. To inoculate the raspberries, 25 μL of inoculum were deposited on the skin of each fruit. For strawberries, 50 μL of inoculum were deposited on the skin of each strawberry, approximately midway between the calyx and cap (Han and others 2004). The fruits remained in a laminar flow hood for 24 h after inoculation to allow for attachment of the microorganisms. Both inoculated raspberries and strawberries had approximately 10^5 CFU/g of both *E. coli* O157:H7 and *Salmonella*.

Treatment with pulsed UV-light

Pulsed UV-light was produced using a laboratory scale, batch-fed pulsed-light system (Figure 1, Steripulse-XL 3000, Xenon Corp., Wilmington, Mass., U.S.A.). The system generated 1.27 J/cm^2 per pulse for an input of 3800 V and with 3 pulses per second setting at 1.8 cm from the quartz window according to the manufacturer's specifications. It should be noted that the distance between the UV-strobe and the quartz window was 5.8 cm. The lamp produced polychromatic radiation in the wavelength range of 100 to 1100 nm, with 54% of the energy being in the UV-light region (Panico 2002). Fruits were treated at 3 different distances as measured from the bottom of the fruit to the bottom of the quartz window: 3, 8, and 13 cm for raspberries and 5, 8, and 13 cm for strawberries. For strawberries, a distance of 5 cm was used instead of 3 cm because at that height the system could not accommodate the fruits due to their larger size. At each distance from the quartz window, 5-, 10-, 30-, 45-, and 60-s treatment times were evaluated. Furthermore, the temperature just under the surface of the fruit was monitored using a K-type thermocouple (Omegaette HH306, Omega Engineering

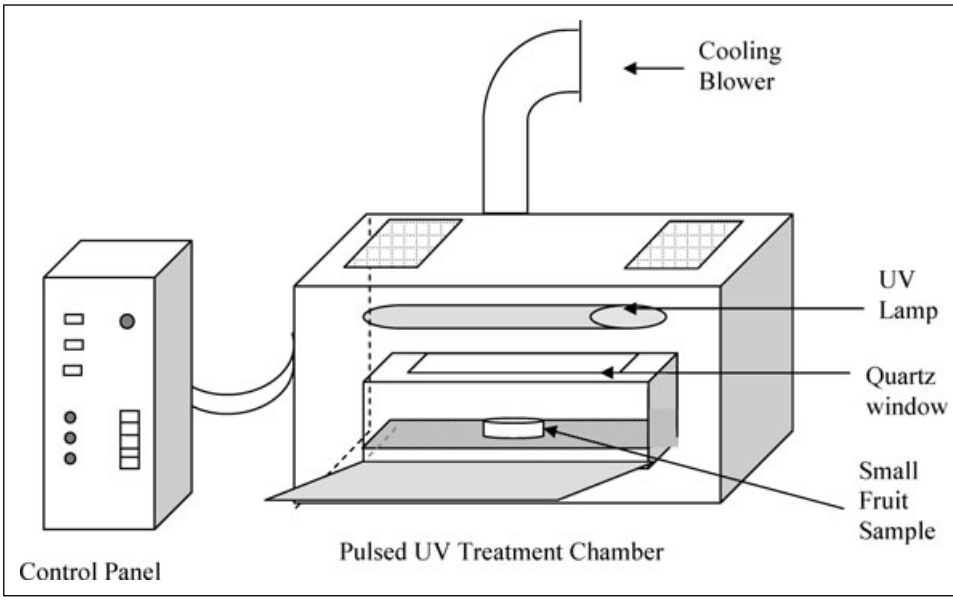

Figure 1 — Schematic of pulsed UV setup.

Inc., Stamford, Conn., U.S.A.) by placing the thermocouple 1 to 2 mm under the surface of the fruit. The broadband energy at each level was also measured at each treatment level using a Nova Laser Power energy monitor (Ophir Optronics Ltd., Wilmington, Mass., U.S.A.), which averaged the energy level across 30 pulses.

Thermal inactivation of *E. coli* O157:H7 and *Salmonella*

A significant increase in the temperature of the fruit was observed after treatment with pulsed UV-light at closer distances to the light and longer treatment times. The effect of heat alone was investigated using a water bath study. A cocktail of either *E. coli* O157:H7 or *Salmonella* was prepared by growing cultures in 10 mL of TSBN for 24 h; the cultures were then combined and centrifuged for 15 min at 3300 × *g* and 4 °C. The supernatant was then decanted and the cultures were resuspended in 10 mL of phosphate buffer. A 50-mL sample of phosphate buffer was placed in a sterile 250-mL beaker (Kimax Model nr 1400, VWR Intl., West Chester, Pa., U.S.A.) and was inoculated with 1 mL of either *E. coli* O157:H7 or *Salmonella* cocktail and immediately placed in the water bath (Aquabath Model nr 18800; Labline Instruments Inc., Melrose Park, Ill., U.S.A.), which was being maintained at room temperature. The inner diameter of the beaker was approximately 6.5 cm, and the depth of the buffer was approximately 1.7 cm. Furthermore, the water in the bath was kept at least 1 cm above the buffer surface in the beaker to ensure that the buffer was always surrounded by hot water. The water bath was turned on at a setting of 87 °C and the temperature was allowed to rise, while the temperatures of the bath and the buffer were monitored. Samples of 1 mL were taken at 2, 4, 8, 16, 32, and 64 min and analyzed for surviving microbial populations.

Microbial analysis

After treatment, strawberries were placed in 50 mL of Dey-Engley Neutralizing (D/E) Broth (Difco) and raspberries were placed in 25 mL D/E broth and pummeled for 1 min in a stomacher. The homogenate was then serially diluted in 0.1% peptone water (Difco) and spiral plated on tryptic soy agar (Difco) supplemented with 50 μg/mL of nalidixic acid with an Autoplate 4000 (Spiral Biotech, Norwood, Mass., U.S.A.). Plates were incubated at 37 °C for 24 h and then enumerated using Q-count (version 2.1, Spiral Biotech). Reductions of bacteria were calculated on a per gram of fruit basis. Random colonies of *E. coli* O157:H7 and *Salmonella* were confirmed serologically using RIM *E. coli* O157:H7 latex test (Remel Microbiology Products, Lenexa, Kans., U.S.A.) and *Salmonella* O antiserum A-1 latex agglutination test (Remel).

Quality analysis

As a preliminary measurement of fruit quality, immediately after pulsed UV-light treatment, a color analysis was performed on fruits from the treatment with the highest microbial reduction. A Minolta Chromo Meter CR200 colorimeter (Minolta, Ramsey, N.J., U.S.A.) was used to measure the L^*, a^*, b^* color space. The color space uses the following parameters: L^* indicates the lightness, and a^* and b^* are the chromaticity coordinates. Value $-a^*$ indicates a green color, $+a^*$ a red color, $-b^*$ a blue color, and $+b^*$ a yellow color. Prior to use, the chromameter was calibrated using a white tile. Three randomly selected spots were analyzed and averaged to get an overall measurement for each fruit and replicated 3 times.

Statistical analysis

All experiments were replicated 3 times, and MINITAB (version 14, MINITAB, State College, Pa., U.S.A.) statistical software was used to analyze the mean $\log_{10}$ reductions. A 1-way analysis of variance (ANOVA) with a 95% confidence level was used to compare the treatment times from a given distance from the UV-light. A Tukey's comparison was also performed to determine significant differences using a P value less than or equal to 0.05. Furthermore, a general linear model was used to determine the significant factor involved in inactivation and determine if there was any interaction between factors.

Results and Discussion

Treatment of raspberries

Raspberries inoculated with *E. coli* O157:H7 and *Salmonella* were treated with pulsed UV-light at fluencies of 0.19, 0.33, and 0.40 J/cm^2/pulse, which corresponded to 13, 8, and 5 cm from the quartz window, respectively. Raspberries were treated at times of 5, 10, 30, 45, and 60 s, which resulted in total maximum broadband energy doses of 34.2, 59.4, and 72 J/cm^2 for 13, 8, and 5 cm, respectively.

Reductions of *E. coli* O157:H7 were between 0.4 and 3.9 $\log_{10}$ CFU/g at fluencies of 2.9 and 72 J/cm^2, respectively (Table 1). At a distance of 3 cm from the quartz window, reductions ranged between 0.9 and 3.9 $\log_{10}$ CFU/g at 5 and 60 s, respectively. ANOVA analysis indicated that a treatment of 60 s resulted in significantly higher $\log_{10}$ reductions than the lower treatment times. Slightly lower $\log_{10}$ reductions were observed at treatments conducted at 8 cm from the quartz window; reductions were between 0.7 and 3.0 $\log_{10}$ CFU/g at 5 and 60 s, respectively. The treatment at 8 cm for 60 s resulted in a significantly higher $\log_{10}$ reduction (3.0 $\log_{10}$ CFU/g) than the other treatment times. The final treatment distance was 13 cm from the quartz window, which resulted in reductions of 0.4 and 2.6 $\log_{10}$ CFU/g at 5 and 60 s, respectively. Again, the 60-s treatment produced significantly higher $\log_{10}$ reductions than the lower treatment times.

An ANOVA using a general linear model indicated that both distance from the quartz window and treatment time were significant factors in the inactivation of *E. coli* O157:H7 on raspberries, but there was no significant interaction. The analysis was also used

Table 1 — $\log_{10}$ reductions of *E. coli* O157:H7 and *Salmonella* on raspberries after pulsed UV-light treatment.

Distance from quartz window[a]	Treatment time (s)	Broadband energy dose (J/cm^2)	$\log_{10}$ reduction[b,c,e]	
			E. coli O157:H7	*Salmonella*
3 cm	5	6.0	0.9 ± 0.4A	1.0 ± 0.0A
	10	12.0	1.2 ± 0.1 A	1.2 ± 0.2A
	30	36.0	2.0 ± 0.5A	1.8 ± 0.2A
	45	54.0	2.1 ± 0.5A	2.4 ± 0.6AB
	60	72.0	3.9 ± 0.9B	3.4 ± 1.3B
8 cm	5	4.9	0.7 ± 0.2A	1.2 ± 0.3 A
	10	9.9	0.7 ± 0.4A	1.2 ± 0.2A
	30	29.7	1.5 ± 0.3A	1.7 ± 0.3A
	45	44.5	1.5 ± 0.2A	1.9 ± 0.2A
	60	59.4	3.0 ± 0.6B	3.4 ± 0.9B
13 cm	5	2.9	0.4 ± 0.3A	0.3 ± 0.1 A
	10	5.7	0.9 ± 0.4B	0.6 ± 0.1A
	30	17.1	1.6 ± 0.3B	1.1 ± 0.5A
	45	25.7	1.5 ± 0.3B	2.2 ± 0.1B
	60	34.2	2.6 ± 0.2C	2.9 ± 0.5B

[a] Distance from quartz window to UV strobe is 5.8 cm.
[b] Average weight of raspberries is 17.5 ± 2.5 g.
[c] Within the same column and microorganism, values not followed by the same letter are significantly different ($P < 0.05$).
[d] Original populations of 10^6 CFU/g.

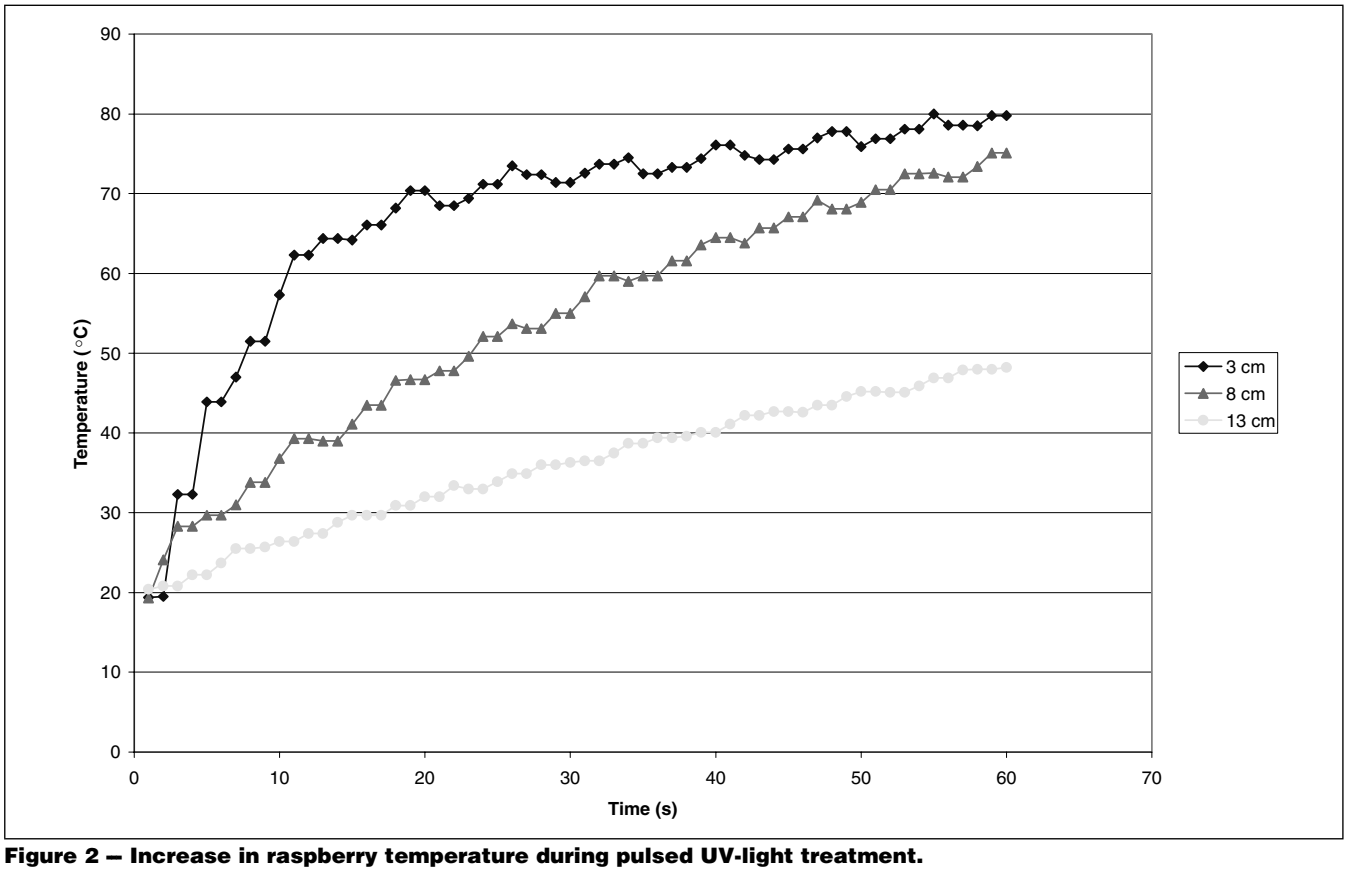

Figure 2 — Increase in raspberry temperature during pulsed UV-light treatment.

to compare reductions at the 3 treatment distances, and it was concluded that a distance of 3 cm resulted in significantly higher $\log_{10}$ reductions than the 8- and 13-cm distances. However, there was no significant difference between reductions at 8 and 13 cm from the quartz window.

Reductions of *Salmonella* were 0.3 to 3.4 $\log_{10}$ CFU/g at fluencies of 2.9 to 72 J/cm^2, respectively (Table 1). At a distance of 3 cm from the quartz window, reductions were between 1.0 and 3.4 $\log_{10}$ CFU/g at 5 and 60 s, respectively. ANOVA analysis indicated that a treatment of 60 s resulted in significantly higher $\log_{10}$ reductions than the lower treatment times. Reductions at 8 cm from the quartz window were between 1.2 and 3.4 $\log_{10}$ CFU/g for 5- and 60-s treatments, respectively. At this treatment distance, a time of 60 s produced significantly higher $\log_{10}$ reductions than other treatment times. The lowest treatment distance, 13 cm, resulted in reductions between 0.3 and 2.9 $\log_{10}$ CFU/g for 5- and 60-s treatments, respectively. A general linear model was used to determine if distance, time, and an interaction between distance and time were significant factors in the reduction of *Salmonella* on raspberries. From this analysis, it was concluded that only time was a significant factor and that distance and distance $*$ time were not significant. From this analysis, it was concluded that the "best" treatment was at 8 cm from the quartz window with a treatment time of 60 s, which resulted in a reduction of 3.4 $\log_{10}$ CFU/g.

Finally, it should be noted that there was a significant increase in the temperature of the raspberry after pulsed UV treatment at all distances from the light. Maximum increases of 60, 55, and 30 °C (fruit temperatures of 80, 75, and 48 °C) were observed at 3, 8, and 13 cm, respectively, after the 60-s treatment (Figure 2). Thus, it is especially important to note that there is a thermal component to the inactivation of pathogens using pulsed UV-light in addition to the photochemical inactivation.

Table 2 — $\log_{10}$ reductions of *E. coli* O157:H7 and *Salmonella* on strawberries after pulsed UV-light treatment.

Distance from quartz window[a]	Treatment time (s)	Broadband energy dose (J/cm^2)	$\log_{10}$ reduction[b,c,e]	
			E. coli O157:H7	*Salmonella*
5 cm	5	5.4	0.9 ± 0.6A[d]	1.1 ± 0.6A[d]
	10	10.8	1.2 ± 0.1A[d]	1.6 ± 0.6A[d]
	30	32.4	2.3 ± 0.7AB[d]	1.9 ± 0.4A[d]
	45	48.6	2.6 ± 0.3B[d]	2.9 ± 1.0AB[d]
	60	64.8	3.3 ± 0.7B[d]	4.3 ± 1.2B[d]
8 cm	5	4.9	1.3 ± 0.0A	1.1 ± 0.3A
	10	9.9	1.3 ± 0.4A	2.1± 0.0AB
	30	29.7	1.7 ± 0.4A	2.1 ± 0.2AB
	45	44.5	1.7 ± 0.3A[d]	2.6 ± 0.1BC[d]
	60	59.4	2.3 ± 1.1A[d]	3.9 ±1.2C[d]
13 cm	5	2.9	0.8 ± 0.2A	1.1 ± 0.1A
	10	5.7	1.2 ± 0.2AB	1.1 ± 0.5A
	30	17.1	1.5 ± 0.3BC	1.5 ± 0.4A
	45	25.7	2.1 ± 0.2D	2.1 ± 0.3AB
	60	34.2	2.0 ± 0.1CD	2.8 ± 0.6B

[a]Distance from quartz window to UV strobe is 5.8 cm.
[b]Average weight of strawberries between 110 ± 5 g.
[c]Within the same column and microorganism, values not followed by the same letter are significantly different ($P < 0.05$).
[d]Treatments resulted in significant damage to the fruit.
[e]Original populations of 10^6 CFU/g.

Treatment of strawberries

Reductions of *E. coli* O157:H7 and *Salmonella* on strawberries treated with various fluencies of pulsed UV-light can be seen in Table 2. Maximum UV doses were 34.2, 59.4, and 64.8 J/cm^2 at 13, 8, and 5 cm, respectively, after treatment for 60 s. At a treatment level of 5 cm, the highest reductions were observed, but there was

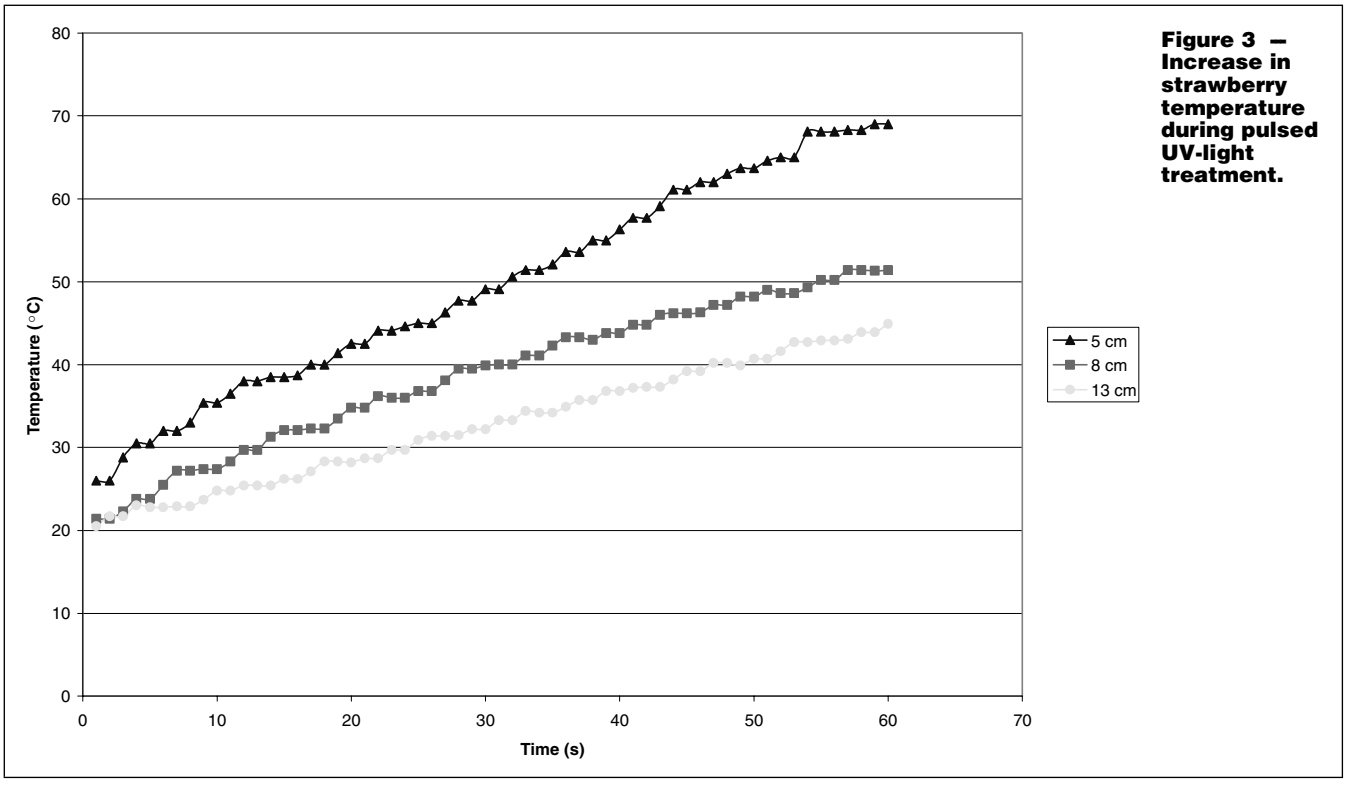

Figure 3 — Increase in strawberry temperature during pulsed UV-light treatment.

significant damage to the calyx of the fruit. Similar damage was observed at 8 cm after 45- and 60-s treatments. Therefore, reductions related to these treatment scenarios are not discussed. Reductions of *E. coli* O157:H7 were 0.8 and 2.1 $\log_{10}$ CFU/g, for 5 and 45 s at 13 cm, respectively. At a distance of 8 cm from the quartz window, reductions were between 1.3 and 1.7 for 5- and 30-s treatments, respectively. There was no significant difference between the reductions obtained at 8 cm. At 13 cm, reductions were between 0.8 and 2.1 for 5- and 45-s treatments, respectively. Analysis indicated that the reduction obtained after 45 s of treatment yielded significantly higher reductions than the lower treatment times. A general linear model was used to determine the significant factors involved in the inactivation of *E. coli* O157:H7 on strawberries. When the reductions resulting from damage to the fruits were removed from the model, the only significant factor in reduction was treatment time; and furthermore, there was no significant difference in the reductions obtained at 8 cm compared to reductions obtained at 13 cm.

Reductions of *Salmonella* at a distance of 8 cm from the quartz window were between 1.1 and 2.1 $\log_{10}$ CFU/g at 5 and 30 s, respectively. There were no treatment times at this distance that resulted in significantly higher reductions, where no damage was observed. At a distance of 13 cm, reductions were between 1.1 and 2.8 $\log_{10}$ CFU/g for 5 and 60 s, respectively. The reduction obtained at 60 s was significantly higher than those between 5- and 30-s treatments; there was no significant difference between reductions at 60 and 45 s, 2.8 and 2.1 $\log_{10}$ CFU/g, respectively. Again, a general linear model was used to determine the significant factors involved in the inactivation of *Salmonella* on strawberries. When the reductions resulting from damage to the fruits were removed from the model, both the distance from the light and the treatment time became significant factors in the inactivation of *Salmonella*. Furthermore, the interaction term was also significant in the model and there was a significant difference between reductions obtained at 8 cm compared to those at 13 cm.

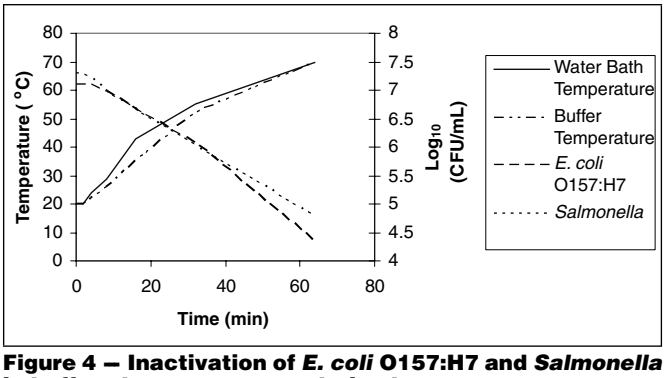

Figure 4 — Inactivation of *E. coli* O157:H7 and *Salmonella* in buffered peptone water during heat treatment.

As with raspberries, there was a significant increase in the temperature of the fruit after treatment with pulsed UV-light. At the treatment times that produced the maximum $\log_{10}$ reductions resulting in no observable damage to the fruit, temperature increases were 18.6 and 24.4 °C (fruit temperatures of 45 and 40 °C) at 8 and 13 cm for 30 and 60 s, respectively (Figure 3).

Thermal inactivation of *E. coli* O157:H7 and *Salmonella*

Buffer solutions inoculated with either *E. coli* O157:H7 or *Salmonella* were heated for 64 min in a water bath as the temperature rose from 20 to 70 °C. The time required to reach a temperature of 70 °C was 64 min, which resulted in reductions of only 2.74 and 2.59 $\log_{10}$ CFU/mL for *E. coli* O157:H7 and *Salmonella*, respectively (Figure 4). This illustrates how much more efficient the heating exhibited in pulsed UV-light treatment is compared to traditional methods of thermal inactivation. It takes only 60 s for the fruit to reach temperatures greater than 70 °C, while it takes over 1 h for phosphate buffer to reach this temperature, and reductions are

much greater with pulsed UV-light. Of course, greater reductions may be possible if a faster rate of heating is employed.

Color measurement

Fruits from the most effective treatments were analyzed immediately after treatment to determine if pulsed UV-light had any negative effects on the color of the fruit as the quality indicator. For raspberries, the treatment that was chosen was the 60-s treatment at 8 cm from the quartz window. The treated raspberries had L^*, a^*, and b^* values of 31.29, +23.16, and +12.99 compared to the untreated raspberries, which had the values of 29.20, +20.25, and +11.66, respectively (Table 3). None of the differences was significant. The treatment used for strawberries was 8 cm, from the quartz window for 30 s. The treated strawberries had L^*, a^*, and b^* values of 30.35, +25.59, and +17.65 compared to the untreated strawberries, which had the values of 33.17, +25.94, and +17.30, respectively. None of the values was significantly different between the treated and untreated strawberries.

There have been few studies evaluating the effects of ultraviolet radiation, in either its continuous or pulsed forms, on the decontamination of pathogenic bacteria on fresh produce. Yuan and others (2003) evaluated continuous UV-C light on the decontamination of *E. coli* O157:H7 and *Salmonella* on the surfaces of apples and tomatoes. Reductions of 3.3 $\log_{10}$ CFU/apple were achieved after treatment with 86.4 J/cm^2 and reductions of 2.19 $\log_{10}$ CFU/tomato of *Salmonella*. The results presented in this study are somewhat comparable. Maximum reductions of *E. coli* O157:H7 and *Salmonella* on raspberries were achieved at UV doses of 72 and 59 J/cm^2, respectively, which resulted in reductions of 3.9 and 3.4 $\log_{10}$ CFU/g, respectively.

There have been several studies looking at the efficacy of sanitizers for the decontamination of pathogens on strawberries. Yuk and others (2006) evaluated chlorine dioxide gas and found a 4.6 $\log_{10}$ CFU/berry reduction after a 1-h treatment. A variety of "wet" sanitizers have been evaluated. Acidic electrolyzed oxidizing water produced a 2.4 $\log_{10}$ CFU/fruit of coliform bacteria (Koseki and others 2001). Yu and others (2001) evaluated sodium hypochlorite (200 ppm), Tween 80 (200 ppm), 5% acetic acid, 5% sodium phosphate, and 3% hydrogen peroxide for the ability to decontaminate *E. coli* O157:H7 on strawberries. These sanitizers produced reductions of 1.34, 1.16, 1.57, 1.58, and 2.15 $\log_{10}$ CFU/g, respectively.

The variations in reductions of microorganisms on the surfaces of raspberries and strawberries can most likely be attributed to shadowing or shielding effects, as described by Lagunas-Solar and others (2006). The presence of achenes on strawberries and the spaces between drupelets on raspberries can shield the microorganisms from the light, leading to only partial disinfection. This shadowing effect may limit the efficacy of pulsed UV-light for the specific purpose of decontaminating raspberries and strawberries. However, as suggested by Lagunas-Solar and others (2006), this shadowing effect may be overcome "by combining a diffuse, multidirectional, intense UV beam with appropriate material handling that ensures even surface exposures."

Another issue, which merits further investigation, is the role of localized heating within the fruit and its impact on inactivation. While the outer surfaces of the fruits did reach upwards of 80 °C, significant inactivations were still observed in fruits that reached no more than 50 °C. For instance, raspberries treated at a distance of 8 cm from the light for 60 s exhibited a $\log_{10}$ reduction of 3.4 CFU/g of *Salmonella* while only reaching a temperature of 50 °C, which is similar to the reduction achieved at 3 cm from the light, which resulted in a temperature of 80 °C (Table 1 and Figure 2).

Table 3 — L^*, a^*, and b^* color readings for raspberries and strawberries after pulsed UV-light treatment.

	Raspberry[a]		Strawberry[b]	
Parameter	Treated[c]	Untreated	Treated[d]	Untreated
L^* value	31.29 ± 3.85	29.20 ± 1.85	30.35 ± 2.39	33.17 ± 1.94
a^* value	23.16 ± 3.93	20.25 ± 2.22	25.59 ± 2.51	25.94 ± 4.15
b^* value	12.99 ± 2.83	11.66 ± 1.68	17.65 ± 2.61	17.30 ± 3.19

[a]Each replication consisted of 9 samples with 2 readings per sample.
[b]Each replication consisted of 3 samples with 2 readings per sample.
[c]Treatment conducted at 8 cm for 60 s.
[d]Treatment conducted at 8 cm for 30 s.

Conclusions

The results presented in this study indicate that pulsed UV-light may be an effective mode of decontamination for small fruits such as raspberries and strawberries. These reductions are comparable to if not greater than reductions obtained via other methods of decontamination. Pulsed UV-light has the added benefit of a relatively short treatment time compared to chemical treatments. Maximum reductions of *E. coli* O157:H7 and *Salmonella* were achieved after 60 s of pulsed UV-light treatment. Reductions of 3.9 and 3.4 $\log_{10}$ CFU/g were achieved on raspberries after UV doses of 72 and 59.4 J/cm^2, respectively. On strawberries, reductions of 2.1 and 2.8 $\log_{10}$ CFU/g were achieved after 25.7 and 34.2 J/cm^2 of UV exposure. This study indicates that pulsed UV-light could be an effective decontamination agent for raspberries and strawberries; however, more studies need to be conducted on the quality and sensory characteristics of the fruits after treatment with pulsed UV-light.

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