EFFECTIVENESS OF UV LIGHT AS A MEANS TO REDUCE *SALMONELLA*
CONTAMINATION ON TOMATOES AND FOOD CONTACT SURFACES

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Running title: UV treatment to reduce *Salmonella* contamination on tomatoes

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Abstract

The effectiveness of ultraviolet light at a wavelength of 254 nm to reduce *Salmonella* contamination on tomatoes and food contact surfaces was evaluated. Inoculated tomatoes were exposed to UV-C light at doses ranging from 0 to 223.1 mJ/cm². All UV treatments significantly reduced *Salmonella* populations ($p < 0.05$). The effectiveness of UV-C light in reducing *Salmonella* contamination on different locations on tomato surfaces under various UV doses (0-117.2 mJ/cm²) was also explored. Results indicated that regardless of the locations, UV treatment was shown to be effective in decreasing *Salmonella* populations. Subsequent studies evaluated possible photoreactivation or dark repair of injured *Salmonella* post-UV treatment. Following UV light exposure at doses of 0, 22.3, 44.6, and 89.2 mJ/cm², tomatoes were either exposed to visible light for 0, 3, and 5 h or stored in the dark for the same amount of time. Photoreactivation was not detected, nor was dark repair. UV light was also evaluated for its effectiveness to reduce *Salmonella* contamination on food contact surfaces (stainless steel, HDPE, waxed cardboard and PVC). Contaminated coupons were exposed to UV-C light at 0, 3.3, and 19.7 mJ/cm². Significant differences were observed between coupons treated with UV light and the controls ($p < 0.05$). Coupons exposed for longer time had greater *Salmonella* population reductions, except for waxed cardboard coupons. Application of UV-C light to reduce *Salmonella* contamination in tomato handling facilities is feasible.

Keywords: UV-C light, *Salmonella*, tomatoes, food contact surfaces

1. Introduction

The frequency of reported foodborne illness outbreaks linked to fresh produce has increased in recent decades. This increase may be due to increased surveillance and increased consumption of fresh produce (Doyle & Erickson, 2008). Since most fresh produce is consumed raw or minimally processed, pathogen contamination may be a potential threat to human health. From 1990 to 2005, produce outbreaks were responsible for 13% of all foodborne outbreaks and 21% of all foodborne illnesses (DeWaal & Bhuiya, 2007). A more recent report, analyzing outbreaks from 1998-2007, indicated that produce outbreaks caused 15% of all foodborne outbreaks and 23% of all foodborne illnesses ([Center for Science in the Public Interest, 2009](#)).~~CSPI~~. Most of the produce-associated outbreaks and illnesses were associated with greens-based salads, cantaloupes, tomatoes, lettuce, and sprouts (Olaimat& Holley, 2012).

Salmonella is one of the primary pathogens associated with produce outbreaks and accounts for 17% of the produce outbreaks during 1998 and 2007 ([Center for Science in the Public Interest, 2009](#)).~~CSPI~~. Produce items associated with outbreaks of salmonellosis include sprouts, greens-based salad, melon, and potatoes (DeWaal & Bhuiya, 2007).

The first large multistate *Salmonella* outbreaks related to tomato consumption were reported back in 1990 (Hedberg et al., 1999). The tomato contamination source implicated in at least two outbreaks, involving *Salmonella* Javiana and *Salmonella* Montevideo, was traced to tomato packinghouses (CDC, 2005). Results of a study done by Allen et al., (2005) indicated that *Salmonella* can survive on tomato surfaces and packing line surfaces under common environmental conditions.

Interventions are needed to minimize pathogen contamination of raw produce and to eliminate them if present on produce. Normally, fresh produce receives little microbial

intervention other than washing. For these reasons, alternative strategies to decrease pathogenic bacterial levels on fresh produce are needed. One of the alternatives is to use ultraviolet-C (UV-C) light at 254 nm.

UV light is used for air, water/liquid, and surface decontamination treatments (Bintsis et al., 2000). Its application has been limited due to the poor penetration capabilities of the UV wavelengths and shadowing effects (Sizer & Balasubramaniam, 1999). UV's effectiveness to reduce bacterial contamination on produce has been documented (Chun et al., 2010; Escalona et al., 2010; Sommers et al., 2010; Yaun et al., 2004). Mukhopadhyay et al., (2013) found that UV in combination with low dose gamma irradiation doses resulted in <4 log reduction of *E. coli* and *Salmonella* on grape tomatoes. UV light is also effective in reducing black mold, gray mold, and *Rhizopus* soft rot on tomatoes. Treated tomatoes were firmer and had slower ripening, indicating extended shelf life (Lui et al., 1993). UV light offers some other advantages as it does not leave any residue, it does not have legal restrictions, it does not require installation of extensive safety equipment (Wong et al., 1998; ~~Yousef & Marth, 1988~~), it is easy to use, and it is economical (Bintsis et al., 2000). Microbial inactivation is caused by the cross-linking of pyrimidine dimers in DNA which prevents microbial reproduction (Sizer & Balasubramaniam, 1999).

However, many microorganisms have developed mechanisms to repair the UV-induced DNA damage. One of the repair mechanisms is photoreactivation. Photoreactivation is a light-dependent process which involves photolyase to reverse UV-induced DNA damage (Harm, 1980). Therefore, photoreactivation increases the possibility that microorganisms might regain viability after UV light treatment and thus raise food safety concerns. Photoreactivation of fecal coliforms and *E. coli* has been reported (Hallmich & Gehr, 2010; Sommer et al., 2000; Tosa & Hirata, 1999; Zimmer & Slawson, 2002). Hu et al., (2012) found that *Salmonella* Typhimurium,

Shigella dysenteriae, and *E. coli* are able to photoreactivate after UV treatment. Meanwhile, Kuo et al., (1997) did not notice photoreactivation of *S. Typhimurium* on shell eggs.

There are some uncertainties concerning the effectiveness of UV light on reducing *Salmonella* contamination on mature green tomatoes and whether photoreactivation of UV-injured *Salmonella* on tomatoes occurs. If UV light is applied to tomatoes in a processing line, it is likely that not all spots on the tomatoes will be directly exposed to the UV light as tomatoes will be rolling on the conveyer belt. Thus, effectiveness of UV-C light in reducing *Salmonella* contamination on different locations on tomato surfaces needs to be determined. In addition, efficacy of UV light in reducing *Salmonella* contamination on food contact surfaces commonly encountered in tomato handling facilities is also of interest. Thus, the objectives of this study were: (1) to determine the effectiveness of UV-C light in reducing *Salmonella* populations on tomatoes; (2) to evaluate the effectiveness of the treatment to reduce *Salmonella* contamination regardless of its location on the tomato surface; (3) to determine whether photoreactivation by the visible light or the dark repair mechanisms can result in the recovery of damaged *Salmonella* cells post-UV treatment; and (4) to study the effectiveness of UV light to decrease *Salmonella* contamination on food contact surfaces that could be used in tomato handling facilities.

2. Materials and Methods

2.1. Bacterial Cultures and Growth Media

Rifampicin resistant *Salmonella enterica* serovars Michigan (cantaloupe isolate), Montevideo (human isolate from a tomato outbreak), Newport (environmental isolate from a Virginia tomato outbreak), Poona (human isolate from a cantaloupe outbreak), and Saintpaul (orange juice isolate) were obtained from the Citrus Research and Education Center, University of Florida, Lake Alfred, FL (~~Table 1~~) and were adapted to 100 µg/ml of rifampicin. All strains

were preserved on Microbank beads (Microbank; Pro-Lab Diagnostics, Austin, TX) at -80°C. Prior to use, each strain was activated by three successive transfers into 9 ml tryptic soy broth (Becton, Dickinson and Company, Sparks, MD) containing 100 µg/ml of rifampicin (Cat. # BP2679-5; Fisher Scientific, Pittsburgh, PA) for 24 h at 35°C. Rifampicin stock solution was prepared by dissolving 1 g of rifampicin in 20 ml of methanol (Cat. # A412SK-4; Fisher Scientific, Pittsburgh, PA) and filtered through 0.22 µm Millipore Express® PLUS Membrane (Cat. # SCGP00525; Millipore Corporation, Billerica, MA).

On the day of the experiment, 2 ml of each *Salmonella* serovar were combined to produce a 10 ml *Salmonella* cocktail. The 10 ml *Salmonella* cocktail was centrifuged for 10 min at a relative centrifugal force (RCF) of 2,500 x g (Model 5681; Forma Scientific, Inc., Marietta, OH) and the supernatant was decanted. The pellet was washed twice with 10 ml of 0.1% peptone water (Becton, Dickinson and Company, Sparks, MD) and resuspended in 10 ml of 0.1% peptone water for final use. Tryptic soy agar (TSA; Becton, Dickinson and Company, Sparks, MD) with 100 µg/ml rifampicin (TSAR) was used to enumerate *Salmonella*. Resuspended cultures were serially diluted with 0.1% peptone water and enumerated to verify the initial concentration. Resuspended cultures contained approximately 10⁸-10⁹ CFU/ml *Salmonella*.

2.2. UV-C Light Source

The UV-C light source (American Air & Water, Inc.; Hilton Head Island, SC) was a closed end reflector (CE) germicidal fixture, CE-36-2, with two germicidal (254 nm) slim line (GML005) lamps. The dimension of the CE fixture is 94 x 18 x 19 cm. The UV lamp fixture was mounted horizontally by adjustable, tripod style legs. The UV-C lamp apparatus and exposure area was enclosed with sidings lined with aluminum foil to increase the containment of the UV light. The surface on which the samples were placed was covered with bench coat (Versi-Dry

Lab Soakers; Fisher Scientific, Pittsburgh, PA). The intensity of the UV-C light was measured using a Newport power meter model 1928-C (Newport Corporation, Irvine, CA). The UV-C light was allowed to warm up at least 30 min prior to use.

2.3. Effectiveness of UV-C Light (254 nm) in Reducing *Salmonella* Contamination on Tomatoes under Varying UV-C Doses

Mature, unwaxed green tomatoes were obtained from a local distributor. Tomatoes were stored at 4°C until used and allowed to equilibrate to room temperature for approximately 1 h before inoculation. Tomatoes were spot inoculated (Beuchat et al. 2001) with 100 µl of *Salmonella* cocktail within marked areas (~ 6 cm²) on the equatorial plane of each tomato. After inoculating, tomatoes were air-dried for approximately 2 h in a biological safety cabinet before exposing to UV-C light. Positive control tomatoes which were not UV treated were sampled to determine the initial *Salmonella* inoculation level. Negative control tomatoes were not inoculated with the *Salmonella* cocktail.

Tomatoes were placed so the inoculated areas were directly exposed to UV light for 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, and 300 s. The average intensity of the UV light was 743.6 µW/cm². The corresponding doses were 0, 22.3, 44.6, 66.9, 89.2, 111.5, 133.9, 156.1, 178.5, 200.8, and 223.1 mJ/cm². The distance between the center of the light and top of tomato was approximately 53.3 cm.

Treated tomatoes were placed in individual sterile stomacher bags containing 20 ml of universal preenrichment broth (Becton, Dickinson and Company, Sparks, MD). Tomatoes were manually shaken for 30 s, hand-rubbed for 30 s at the inoculation spot, and shaken for another 30 s. Serial dilutions were made using 9 ml of universal preenrichment broth and dilutions were spiral plated (Autoplate 4000; Spiral Biotech, Inc., Bethesda, MD) onto TSAR. The detection

limit was 200 CFU/ml. All plates were incubated at 35°C for 24 h before enumerating surviving *Salmonella*. Negative control tomatoes were plated on both TSA and TSAR plates to check for background microflora.

2.4. Evaluation of Whether the Orientation of *Salmonella* Contaminated Tomatoes Influences the Effectiveness of UV-C Light

Inoculation of mature green tomatoes was the same as described previously. Six tomatoes with *Salmonella* inoculated on the same spot of tomato surface, were positioned differently under UV-C light to evaluate the effectiveness of the treatment to reduce *Salmonella* contamination regardless of its location on the tomato surface (whether it was directly or indirectly exposed to the UV light) for each replication (Fig. 1). The average intensity of the UV light at those 6 spots was 651 $\mu\text{W}/\text{cm}^2$. Tomatoes were exposed at doses of 0, 19.5, 39.1, 58.6, 78.1, 97.6, and 117.2 mJ/cm^2 for 0, 30, 60, 90, 120, 150, and 180 s. The distance between the center of the light and the tomato surface was kept the same as in the previous study. Recovery of *Salmonella* from tomatoes was done in the same manner as mentioned previously, except that dilutions were spread plated instead of spiral plated.

2.5. Evaluation of Possible Photoreactivation of Injured *Salmonella* Post-UV-C Treatments

This study determined the possibility of repair of injured *Salmonella* post-UV-C treatments with visible light. Inoculated mature green tomatoes were exposed directly to UV-C light at various doses of 0, 22.3, 44.6, and 89.2 mJ/cm^2 for 0, 30, 60, and 120 s at a distance of approximately 53.3 cm from the tomato surface. Following UV-C exposure, tomatoes were exposed to visible light from 8 fluorescent lamps in a chamber (Percival model E-41 HO; Percival Scientific, Inc., Perry, IA). The intensity of the visible light was approximately 10

mW/cm² measured with Newport power meter model 1928-C. The inoculated tomatoes were exposed to the lamps for 0, 3, and 5 h. The distance between the light source and tomato surface was approximately 43.8 cm. The temperature of the chamber was 20°C (±0.5°C).

To determine if recovery under darkness occurred, inoculated tomatoes treated after UV-C light treatment were stored in the dark in stainless steel containers for 0, 3, and 5 h at room temperature, 19-20.5°C. Subsequent to the respective visible light and dark exposure, treated tomatoes were placed in individual sterile stomacher bags containing 20 ml of universal preenrichment broth and sampled for surviving *Salmonella* as previously described.

2.6. Effectiveness of UV-C light (254 nm) in Reducing *Salmonella* Contamination on Food Contact Surfaces under Varying UV-C Doses

Four food contact surfaces (stainless steel, high density polyethylene, polyvinyl chloride, and waxed cardboard) were chosen to simulate the contact surfaces that could commonly be used in commercial tomato facilities. Stainless steel coupons (SS; type 304, finish #4B, 0.9 mm thick) sized (30 x 50 mm) with smooth edges were fabricated by University of Georgia Instrument Shop, Athens, GA. Stainless steel coupons were autoclaved before use. High density polyethylene (HDPE; 2 mm thick; United States Plastic Corporation, Lima, OH) and polyvinyl chloride (PVC) belting (3 mm thick; # 120 white; W.L. Deckert Company, Inc., Milwaukee, WI) were cut to size (30 x 50 mm) using scissors and a utility knife, respectively. The cut coupons were used one time and autoclaved before use. Waxed cardboard (WC; 4 mm thick; International Paper Company, Griffin, GA) was cut to size (30 x 50 mm) using a scalpel. Waxed cardboard coupons were sterilized by spraying 70% ethanol (Decon Laboratories, Inc., King of Prussia, PA) over the front and back sides of the cardboard pieces. After 30 s exposure, the ethanol was

wiped from coupon surfaces using a sterile Whirl-PaK® Speci-Sponge® Environmental Surface Sampling Sponge (38 x 76 mm; Nasco, Fort Atkinson, WI) wetted with sterile DI water.

All four types of coupons were placed in sterile metal pans and the surfaces were spot inoculated with 100 µl of the resuspended *Salmonella* cocktail. Inoculated coupons were air-dried in a biological safety cabinet for 90 min. Positive UV-control coupons did not receive UV-C treatments. Negative control coupons were not inoculated. Three inoculated coupons of each type of surface were aseptically placed under UV-C light and exposed to UV-C light at an intensity of 656 µW/cm² for 0, 5 (3.3 mJ/cm²) and 30 s (19.7 mJ/cm²) at a distance of 61.6 cm. The 5 s and 30 s treatments were done on separate days.

After the UV treatment, treated coupons were aseptically placed in individual sterile stomacher bags containing 20 ml of universal preenrichment broth. Treated coupons were hand-rubbed for 30 s. Serial dilutions were made using 9 ml of universal preenrichment broth and dilutions were spread plated onto TSAR. All plates were incubated at 35°C for 24 h. Positive UV-control coupons were plated to determine initial concentration of *Salmonella* cocktail on coupons, and negative control coupons were also plated on both TSA and TSAR plates to check for background microflora.

2.7. Statistical Analysis

Experiments with tomatoes and food contact surfaces were replicated three times, with the exception of the first experiment, in which 8 repetitions were performed. Survival of *Salmonella* (CFU/tomato or CFU/coupon) was converted to log₁₀. Statistical analysis was performed using SAS 9.3 (SAS Institute, Inc., Cary, NC). Analysis of variance was carried out by the general linear models (GLM) procedure. When differences among treatments existed (p<0.05), Tukey's multiple comparison method was used to determine the difference.

3. Results and Discussion

3.1. Effect of UV-C Light in Reducing *Salmonella* Contamination on Tomatoes

The efficacy of UV-C light in inactivating *Salmonella* on green tomatoes was evaluated. *Salmonella* populations inoculated on tomatoes significantly decreased ($p < 0.05$) by 3.22 logs after UV treatment for 30 s (22.3 mJ/cm^2). A maximum reduction of 4.39 log CFU/tomato was obtained when inoculated tomatoes were exposed for 240 s, a UV dose of 178.5 mJ/cm^2 (Fig. 24). Thirty seconds and sixty seconds of exposure were not significantly different from each other. After 90 s of exposure, there was no further significant reduction. No *Salmonella* was detected from the negative controls, indicating the reductions noted were those of the challenge inoculum. Doyle and Erickson (2008) stated that interventions applied to produce should inactivate enteric pathogens by at least 3 logs. The results in this study showed that a 3 log reduction was achieved even with the lowest UV dose. Therefore, UV light can be an alternative intervention to inactivate pathogens on produce.

In a study by Yaun et al., (2004), the populations of *Salmonella* on inoculated tomatoes, which were obtained from a local distributor, were reduced by 2.19 log CFU/tomato when a maximum UV-C dose of 24 mJ/cm^2 was applied. Sommers et al., (2010) reported that *Salmonella* spp. inoculated on the surface of Roma tomatoes (maturity level not mentioned) were inactivated by 3.1 log CFU/g at a dose of 500 mJ/cm^2 . A higher log reduction, 3.8 log CFU/g, was obtained when UV-C dose of $4,000 \text{ mJ/cm}^2$ was used. The authors stated that the higher log reductions were below the detection limit. Song et al., (2011) found that UV-C at 5 kJ/m^2 (500 mJ/cm^2) significantly decreased *S. Typhimurium* on light red cherry tomatoes by 2.58 logs. Yun et al., (2013) reported an initial decrease of 1 to 2 logs of *E. coli* O157:H7 and *Salmonella* on contaminated apricots after treatment with UV-C and noted that surviving populations decreased

at a faster rate than non-UV exposed populations. Bermudez-Aguire & Barbosa-Canovas (2013) found that inactivation of *E. coli* varied depending on the type of contaminated produce that was exposed to UV-C with the greatest reduction noted on the smooth surface of tomatoes. Williams et al., (2012) showed that combining pulsed UV treatments with sanitizers enhanced the reduction in *Salmonella* contamination on tomatoes. Hadjok et al. (2008) used UV light in combination with hydrogen peroxide to reduce *Salmonella* on fresh produce surfaces by at least 4 logs and internalized *Salmonella* by at least 2.8 logs.

Differences in the log reductions between this study and others may be due to using different strains of pathogens with varying levels of UV-sensitivity and UV-C sources of varying efficiencies. Shechmeister (1976) noted that UV sensitivities of bacteria vary not only among species, but also among strains of the same species. In addition, in some cases, the initial inoculum levels were not large enough to obtain greater log reduction calculations than those reported after UV treatment. For example, Sommers et al., (2010) obtained greater than 3 a *Salmonella*-log CFU reduction of *Salmonella* on tomatoes 3.08 CFU/g when exposed to UV at a dose of 500 mJ/cm². When, but even when a four-fold greater dose was applied, there was no significant increase in the log reduction. This study demonstrates that UV light had great efficiency in reducing *Salmonella* populations on tomatoes. The effectiveness of UV-C in reducing microbial growth in baby spinach, lettuce, melon, and fresh-cut apple has also been reported (Allende & Artes, 2003; Allende et al., 2006; Escalona et al., 2010; Manzocco et al., 2011a & Manzocco et al., 2011b).

3.2. Orientation of *Salmonella* Contaminated Tomatoes under UV-C Light

Statistically, there was no difference in the level of *Salmonella* reduction regardless of interaction between the UV treatment and the locations of *Salmonella* on tomato surfaces.

~~meaning that~~ UV at ~~all tested doses~~~~a certain dose~~ exhibited the same statistical pattern regardless of *Salmonella* locations on tomatoes ~~and vice versa~~. After UV exposure, *Salmonella* populations were reduced ($p < 0.05$) to similar levels regardless of the location of the *Salmonella* contamination on the tomato surface (Fig. ~~32~~). There was no significant difference in population reduction for the 30-120 s of exposures. ~~While a similar level of *Salmonella* inactivation was obtained for the various contamination locations on the tomatoes, the population on position 1, facing directly to the UV light source, was reduced significantly more than several of the positions (#3, 4, and 5).~~ UV radiation was effective in reducing *Salmonella* contamination regardless of its location on tomato surfaces. Therefore, if UV treatment is applied to harvested tomatoes rolling on conveyer belts in a processing line, pathogen reduction on the tomatoes is possible. To ensure that tomatoes receive adequate UV treatments, the speed of the conveyer belt would have to be monitored. Wilson et al., (1997) reported that postharvest decay on apples was reduced when treated with UV light on a processing line. The result in this study might show lower log reduction than the previous study, but more than 3 log reduction was still observed for UV at higher dose.

3.3. Lack of Photoreactivation of Injured *Salmonella* Post-UV-C Treatments

Statistically, there was no ~~relationship~~~~interaction~~ between the UV exposure and the ability of injured *Salmonella* to recover after exposure to visible light. Therefore, significant differences were analyzed only among UV treatment and among visible treatment. *Salmonella* counts after UV radiation were significantly lower than those of controls ($p < 0.05$) (Fig. ~~43~~). Since *Salmonella* population levels on tomato surfaces exposed to visible light for 3 or 5 h were less than those on tomatoes not exposed to visible light, no significant injury repair by photoreactivation by visible light treatments was observed. The lower *Salmonella* population on

those exposed to visible light might be due to the fact that there was limited nutrient availability on the tomato surfaces or the surfaces were too dry to support recovery of *Salmonella*. Lang et al., (2004) found that air drying reduced recovery of *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes* on the surface of tomatoes by more than 1 log, suggesting that bacterial cells may be injured or stressed during desiccation~~dessication~~.

To determine if recovery under darkness occurred, post-UV treated *Salmonella* contaminated tomatoes were stored in closed stainless steel containers. ~~.. (Fig. 4). Since there was a lack of interaction, significant differences were analyzed only among UV treatment and among dark treatment.~~ The results were similar to those of the visible light treatment with *Salmonella* levels reduced significantly ($p > 0.05$) after UV treatment (Fig. 5). The treatments of 3 h and 5 h dark exposure did not result in injury recovery.

Kuo et al., (1997) reported similar results on the lack of repair of UV damage. Their study indicated that neither 1 h of light exposure nor 1 h of dark treatment post-UV treatment significantly influenced the photoreactivation or dark repair ability of *S. Typhimurium* on shell eggs. However, photoreactivation of *S. dysenteriae* and *S. Typhimurium* was detected in a study done by Hu et al., (2012). After UV light treatment, contaminated surface water samples were exposed to a fluorescent lamp with an intensity of 0.066 mW/cm^2 at a wavelength of 360 nm for 3 h. They noticed that photoreactivation decreased significantly with higher UV doses.

Various factors may affect photoreactivation. Lindenauer & Darby (1994) noted that the number of initial pyrimidine dimers formed, the amount of photolyase present, the temperature during the formation of the photoreactivation enzyme and dimer complex, and the dose of photoreactivation radiation could affect photoreactivation. Photoreactivation is dependent on the genetic and physiological state of the exposed cell (Harm, 1980).~~Harm (1980) also pointed out~~

~~that “photoreactivation requires that a cell contain the photoreactivation enzyme and that the extent of repair varies with the genetic and physiological state of the cell”.~~

3.4. Effect of UV-C Light in Reducing *Salmonella* Contamination on Food Contact Surfaces

This study evaluated the efficacy of UV-C light in decreasing *Salmonella* contaminated food contact surfaces (stainless steel, HDPE, waxed cardboard, and PVC) which may be used in commercial tomato facilities. Analysis of UV light exposure for 5 s was done separately from the 30 s UV exposure treatment since the experiments were done on separate days. There were statistical differences~~Statistically, there was interaction~~ ($p \geq 0.05$) in *Salmonella* survival~~onbetween~~ the ~~UV treatment and the four~~ food contact surfaces. However, the four contact surfaces were not ~~statistically~~ compared to each other because one type of material is usually used for a specific application, not interchangeably. For instance, stainless steel, a widely recognized excellent material for the food industry, is usually used in the manufacture of dump tanks, processing lanes, and most equipment in tomato packinghouses (Allen et al., 2005). Meanwhile, PVC is usually used for conveyer belts or to cover roller bars which move tomatoes along the processing lines (Mukhopadhyay & Ramaswamy, 2012). Bins made of HDPE are usually used to gather tomatoes during harvest, and waxed cardboard boxes can be used to pack tomatoes for distribution.

UV exposure for 5 s (3.3 mJ/cm^2) significantly reduced *Salmonella* populations on all food contact surfaces (Fig. 65). *Salmonella* was decreased by 2.75, 2.93, 1.39, and 1.91 log CFU/coupon on SS, HDPE, WC, and PVC, respectively. *Salmonella* log reduction in waxed cardboard was not as great as that on other coupons. Significant differences were also observed between the 30 s of UV treatment and the controls (Fig. 76). Thirty seconds (19.7 mJ/cm^2) of UV

exposure, respectively, resulted in 3.51, 4.32, 1.43, and 3.51 log reductions of *Salmonella* contamination on SS, HDPE, WC, and PVC. When comparing the results of coupons treated for 5 s and 30 s of UV, coupons exposed for longer time had greater *Salmonella* population reductions. Regardless of 5 s or 30 s of UV radiation, *Salmonella* populations decreased the least on waxed cardboard. Yaun et al., (2004) found that microbial populations on the surface of waxed tomatoes were greater than those on the surface of unwaxed apples after UV-C exposure. They assumed that wax applied on the surface of tomatoes might have shielded bacteria from UV radiation.

Sommers et al., (2010) obtained more than 5 log reductions of *Salmonella* spp., *Staphylococcus aureus*, and *Listeria monocytogenes* on electroplated and bead blasted stainless steel coupons when inoculated coupons were exposed to UV-C at a dose of 400 mJ/cm². When inoculated coupons were treated with 50 mJ/cm², the three pathogens were reduced by 1.86-3.05 logs. Sommers et al. (2012) exposed stainless steel and HDPE contact surfaces contaminated with *Francisella tularensis* to UV-C and found that exposure to 0.5 J/cm² reduced the pathogen level by more than 4 logs. Kim et al., (2002) also reported that either intensities of 250 or 500 µW/cm² significantly decreased *L. monocytogenes*, *S. Typhimurium*, and *E. coli* O157:H7 populations on stainless steel chips. Intensity at 500 µW/cm² for 3 min (90 mJ/cm²) reduced populations of the three pathogens by more than 4 logs. Intensity of 250 µW/cm² for 1 min (15 mJ/cm²) decreased the levels of the pathogens by 2.43-4.38 logs. This result is similar to the present findings, in which a 3.51 log reduction was achieved when stainless steel was treated for 30 s at 19.7 mJ/cm². Bae and Lee (2012) demonstrated that UV treatment at intensity 0.236 ± 0.013 mW/cm² for 3 h significantly reduced *S. Typhimurium*, *L. monocytogenes*, and *S. aureus* on stainless steel surfaces by 3.06, 2.18, and 2.70 log CFU/coupon, respectively, and *S. aureus*

on polypropylene by 3.11 logs. They concluded that the effectiveness of the UV treatment depends on the surface material. Haughton et al. (2011) achieved a 4.2 log reduction of *S. Enteritidis* on 9 different food contact surfaces with UV levels from 0.010 to 0.192 J/cm² and found significant reductions in *Salmonella* levels on all the surfaces.

This study indicated that UV-C light was effective in reducing *Salmonella* contamination on tomatoes surfaces and various food contact surfaces. In addition, recovery of UV-C damaged *Salmonella* due to possible photoreactivation or dark repair was not observed. The overall findings of this study indicated that UV treatment is effective in reducing *Salmonella* contamination on food contact surfaces.

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Figure 1. Placement of inoculated tomatoes in the UV chamber. Marked areas indicate the positioning of the inoculated surface in relation to the UV-C light (as viewed from top).

Figure 2. Survival of *Salmonella* on tomato surfaces after UV light treatment at an intensity of $743.6 \mu\text{W}/\text{cm}^2$ for 0 to 300 s. Values with different letters were significantly different ($p < 0.05$).

Figure 32. Survival of *Salmonella* on 6 different locations on the tomato surfaces after treatment of UV light at intensity of $651 \mu\text{W}/\text{cm}^2$ from 0 to 180 s. *Salmonella* contamination positions on tomato surfaces: 1 – directly exposed to UV source; 2 and 5 – on equatorial plane facing reflective side wall of UV protective shield; 3 – on equatorial plane facing tomatoes; 4 and 6 – on equatorial plane facing reflective end walls of UV protective shield.

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Fig. 1

Fig. 2

Fig. 3

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Fig. 7