Inactivation of *Salmonella* Typhimurium in fresh cherry tomatoes using combined treatment of UV–TiO₂ photocatalysis and high hydrostatic pressure

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Abstract The antibacterial efficacy of UV–TiO₂ photocatalysis pre-washing in a water-assisted system (UVT, 4.5 mW/cm², 5–15 min) and high hydrostatic pressure (HHP, 300–500 MPa, 1 min at 25 °C) post-package combined treatment was evaluated against *Salmonella* Typhimurium inoculated onto whole cherry tomato surfaces and compared with chlorine disinfection (200 ppm). An air pump was fitted at the bottom of UVT reactor to create turbulent flow for rotation of fruits for uniform disinfection. UVT–HHP combined treatment at 500 MPa achieved bacterial reduction of more than 5 log via a synergistic effect, compared with chlorine disinfection. Lycopene and total phenolic contents and antioxidant activities were not significantly changed in tomatoes after any treatment. UVT–HHP combined treatment did not affect the surface color but caused softness in tomatoes. UVT pre-washing followed by HHP post-package treatment can be the effective intervention strategy alternative to conventional chlorine disinfection for production of ready-to-eat (RTE) fresh cherry tomatoes.

Keywords *Salmonella* Typhimurium · Cherry tomato · UV–TiO₂ photocatalysis · High hydrostatic pressure

Introduction

Raw agricultural produce is vulnerable to contamination with pathogenic microorganisms from cultivation to the end of the post-harvest chain. Outbreaks associated with tomatoes have been predominantly linked with *Salmonella*, followed by the norovirus and the hepatitis A viruses [1]. There were 15 multi-state outbreaks of illness caused by *Salmonella* contaminated tomatoes with confirmed illness and death in the United States from 1973 to 2010 [2]. Despite severe food safety risks, tomatoes reach consumers without any effective decontamination treatment [3]. Raw cherry tomatoes are consumed fresh in salads, burgers, and pizza toppings due to an attractive appearance and high nutritive value [4]. The shelf stability of this tomato is short, ranging from 5 to 7 days depending on harvest factors, indicating limitations regarding use in fresh markets [3]. Chlorine-based disinfectants are widely used in industrial settings for sanitization of fresh produce. Concerns have been raised about the treatment efficacy and possible production of potential carcinogenic by-products in water during chlorine-based disinfection of fresh produce. There is a global trend for elimination of chlorine from fresh produce disinfection processes. Use of chlorine with minimally processed vegetable products has been prohibited in the European countries of Belgium, Denmark, Germany, and the Netherlands [5, 6].

Both industrial and academic research has focused on development of novel technologies to produce safe and high quality foods to meet demands of modern consumers [7, 8]. Mukhopadhyay et al. [9] reported application of a combination of UV and selected antimicrobial washes against *Salmonella* on tomatoes as a replacement for chlorine disinfection of fresh produce. An in-package cold plasma technique showed potential for decontamination of

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cherry tomatoes while retaining product quality [5]. An in-package aerosolization technology was suggested to improve the microbial safety of cherry tomatoes against *Salmonella* without loss in quality parameters [10].

UV–TiO₂ photocatalysis (UVT) technology has shown potential for disinfection of fresh produce surfaces [8]. In recent years, UVT technology has been reported to overcome limitations of simple UV for disinfection of fresh produce to a better degree than chlorine disinfection [8, 11–13]. Kim et al. [12] reported that UVT effectively reduced natural microflora and inoculated pathogenic bacterial levels of *Escherichia coli*, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Salmonella* Typhimurium on iceberg lettuce than simple UV, and a sodium hypochlorite solution treatment. Cho et al. [11] found that UVT achieved a higher disinfection rate for *E. coli*, *Salmonella* Typhimurium, and *Bacillus cereus* on fresh carrots than simple UV.

Consumer demand for RTE food products has increased in recent years because of the convenience. High hydrostatic pressure (HHP) is a powerful post-packaging decontamination method for production of RTE food products. HHP processing generally involves use of hydrostatic pressures of 100–1000 MPa (145,000 psi) for periods of 30 s up to several minutes mostly using water as a pressure transmission medium at room temperatures to destroy pathogenic and spoilage microorganisms. Foods and final packaging materials are treated together so that an entire pack remains a secure unit until subsequent opening. The shape and integrity of the package remains unchanged since the pressure applied is identical on every part of the product [14]. UVT technology was combined with HHP in this study. Combining technologies allows use of low individual treatment intensities for minimization of processing effects on nutritive values and freshness of food products and for process cost reductions [15, 16].

The objective of this study was evaluation of the efficacy of a UVT and HHP combined treatment against *Salmonella* Typhimurium inoculated onto cherry tomato surfaces. UVT was used as a pre-washing phase followed by HHP as a post-package decontamination method for production of RTE fresh cherry tomatoes for fresh markets. Effects of UVT and HHP combined treatments on nutritional and physicochemical qualities of cherry tomatoes were determined.

Materials and methods

Chemicals

A hypochlorite solution was purchased from Yakuri Pure Chemicals Co. (Kyoto, Japan). Butylated hydroxytoluene

(BHT), 2-diphenyl-1-picrylhydrazyl (DPPH), and Folin–Ciocalteu's phenol were purchased from Sigma-Aldrich (St. Louis, MO, USA). Metaphosphoric acid was purchased from Junsei Chemical Co. (Tokyo, Japan). Acetone and ascorbic acid were obtained from Duksan Pure Chemical Co. (Ansan, South Korea). Gallic acid was purchased from Samchun Pure Chemical Co. (Pyeongtaek, South Korea). All chemicals were of analytical or HPLC grade.

Cherry tomatoes

Cherry tomatoes (*Solanum lycopersicum* L.) were purchased from a local supermarket in Seoul, South Korea. Cherry tomatoes were used as model fresh produce regardless of the cultivar and season. Mature tomatoes of uniform size and free from visible blemishes and decay were washed with tap water. Tomatoes were stored at 4 °C until use within 24 h.

Microbial strain, test culture preparations, and inoculation

Salmonella Typhimurium (ATCC 14028) was obtained from the American Type Culture Collection (Manassas, VA, USA). Difco XLD agar, Difco buffered peptone water, and Bacto tryptic soy broth were purchased from Becton, Dickinson and Company (Sparks, MD, USA). A stock culture of *Salmonella* Typhimurium was prepared in tryptic soy broth after incubation at 38 °C for 24 h with continuous gentle shaking. A 1 mL cell aliquot was transferred to 100 mL of fresh tryptic soy broth and incubated at 38 °C for 24 h with gentle shaking. A cell suspension of the microbial strain was centrifuged at 4000×*g* for 10 min. Then, the cell pellet of each strain was suspended in a 30 mL volume of a 0.85% NaCl solution and used as an inoculum. Tomatoes were taken out of 4 °C storage and allowed to equilibrate to room temperature for about 1 h before inoculation. Tomatoes without stalks were then immersed in the inoculum for 30 s and drained for 1 h to remove excess inoculum. The initial population of *Salmonella* Typhimurium was approximately 5.47 log CFU/mL.

Surface decontamination of cherry tomatoes

Five inactivation treatments were applied. A photocatalytic reactor was customized following a previous study (Fig. 1) [12]. The reactor consisted of a stainless steel vessel, an air pump, and six UV lamps with TiO₂-coated quartz tubes. The air pump was fitted at the bottom of the reactor to create turbulent flow for rotation of fruit for uniform disinfection of fruit surfaces.

Fig. 1 Schematic diagram of a lab scale UV–TiO₂ photocatalytic reactor assembled at Taekyeong UV, Co., Korea. The reactor consisted of a stainless steel vessel with a volume capacity of 30 L, an air pump, and six waterproof 254 nm wavelength UV lamps (35 W, 25 mW/cm²) in 24.5 mm outer diameter TiO₂-coated quartz tubes (0.7–0.9 mm TiO₂ thickness)

1. Water washing as control: Inoculated tomatoes were washed for 0, 5, 10, and 15 min in the reactor containing tap water.
2. Chlorine disinfection: Inoculated tomatoes were treated for 0, 5, 10, and 15 min in the reactor containing a chlorine solution (200 ppm prepared using a 12% hypochlorite solution). A neutralizing step was carried out immediately after treatment by washing chlorine-treated tomatoes in tap water for 1 min.
3. UV simple in water-assisted system: UV lamps without TiO₂-coated quartz tubes were submerged in the reactor containing tap water and inoculated tomatoes were treated for 0, 5, 10, and 15 min.
4. UVT in water-assisted system: UV lamps with TiO₂-coated quartz tubes were submerged in the reactor containing tap water and inoculated tomatoes were treated for 0, 5, 10, and 15 min. The intensity of UV light was 6 mW/cm² for UV and 4.5 mW/cm² for UVT. The lower intensity for UVT treatment was due to TiO₂-coatings on quartz tubes. Waterproof UV lamps in quartz tube units were submerged during the process.
5. HHP: Control tomatoes, 15 min UVT-treated tomatoes, and 15 min chlorine-treated tomatoes were individually packed in flexible polyethylene terephthalate

pouches (10 × 15 cm) with distilled water, followed by heat-sealing with no headspace. Packages of 3 tomatoes in a pack were loaded into the 5 L volume capacity pressure vessel of a hydrostatic pressurization unit (HPP-600, Baotou Kefa Co., Inner Mongolia, China) and pressurized from 300 to 500 MPa for 1 min at 25 °C. The pressure was increased at a speed of 2 MPa/s and the decompression time was 7–8 s. Distilled water was used as a pressure transmission fluid.

Microbiological analysis

The pour plate method was used for enumeration of viable bacterial cells using a selective agar medium before and after treatments. Treated tomatoes were crushed and homogenized using a sterile 0.85 NaCl solution by stomacher for 2 min. Samples were serially diluted using saline solution, followed by inoculation with 1 mL of the solution in duplicate plates containing XLD agar for detection of viable cells after incubation at 37 °C for 24 h. Colonies were counted at the end of the incubation period. Log N/N_0 was calculated for determination of inactivation effects where N represents viable bacterial counts per mL of m after treatment and N_0 represents the initial bacterial count on tomatoes before treatment. The initial population N_0 of *Salmonella* Typhimurium on tomatos surface was 5.47 log CFU/mL.

Determination of lycopene content

The lycopene content was measured following the method described by Ilahy et al. [17] with modification. Briefly, 1 g of homogenized tomatoes was mixed in tubes with 16 mL of a hexane: ethanol: acetone solution (2:1:1, v/v/v) containing 0.05% BHT using a shaking incubator for 1 h at room temperature. Then, 1 mL of deionized water was added to each tube and homogenized tomato samples were shaken for an additional 3 min, then left at room temperature for 10 min to allow separation of phases. The absorbance value of the upper hexane extract layer was measured at 503 nm using a spectrophotometer (UV-MINI1240, Shimadzu Co., Kyoto, Japan). The lycopene content was calculated as Eq. 1:

$$\text{Lycopene (mg/1000 g fresh weight)} = \frac{A_{503} \times 536.9 \times 16 \times 0.5}{172} \quad (1)$$

where A_{503} is the sample absorbance, 536.9 g/mol is the molecular weight of lycopene, 16 mL is the volume of mixed solvent, 0.5 is the volume ratio of the upper layer to the mixed solvents, and 172 mM^{−1} is the molar extinction

coefficient for lycopene in hexane. Results were expressed as mg/1000 g of tomato fresh weight (fw).

Determination of ascorbic acid content

The ascorbic acid content was determined following the HPLC method of Cardoso et al. [18] with modification. Briefly, 5 mL of freshly squeezed tomato was pipetted into a 50 mL centrifuge tube containing 20 mL of 4.5% metaphosphoric acid and centrifuged at $1640\times g$ for 15 min. Then, 0.5 mL aliquot of the supernatant was pipetted into a 10 mL volumetric flask and filled to volume with 4.5% metaphosphoric acid. Next, the flask was shaken for complete mixing and the liquid was filtered through a $0.45\ \mu\text{m}$ nylon filter. A chromatographic system consisting of a UV detector (Dionex Co., Dreieich, Germany) and a reverse phase column ($4.6\ \text{mm} \times 250\ \text{mm}$, Shiseido Co., Tokyo, Japan) was used. Injection of 20 μL was used for standards and samples. Results were reported as mg/100 g of fw. Each sample was prepared and analyzed in triplicate.

Determination of total phenolic contents

Total phenolic contents were measured using Folin–Ciocalteu reagent following Singleton's method [19]. Briefly, 0.5 mL of extract at an appropriate dilution was added to 2.5 mL of Folin–Ciocalteu reagent and 2 mL of a 7.5% sodium carbonate solution. The absorbance value was measured at 760 nm using a spectrophotometer after incubation for 90 min in the dark. The total phenolic content was expressed as mg of gallic acid equivalents per gram of dry weight (mg GAE/g of dw) based on a standard gallic acid curve.

Determination of DPPH radical scavenging activity

The DPPH radical scavenging activity was measured following the method of Kim et al. [20]. Briefly, each test solution including 1 g of tomato and 1 mL of ethanol was mixed with 1 mL of a 0.2 mM freshly prepared DPPH methanol solution. The mixture was left to stand for 30 min in the dark and the absorbance was measured at 517 nm using a spectrophotometer. The percentage of DPPH scavenging activity was expressed as:

$$\text{DPPH inhibition (\%)} = \left[1 - \left(\frac{A_{\text{Experiment}}}{A_{\text{Control}}} \right) \right] \times 100 \quad (2)$$

Color measurements

The tomato surface color was determined using a chromameter based on the Hunter color system (Konica CR-400, Minolta Sensing Inc., Tokyo, Japan). The

chromameter was calibrated using a white tile ($Y = 92.3$, $x = 0.3156$, $y = 0.3433$). Color values were expressed as L^* (lightness, or brightness/darkness), a^* (redness), and b^* (yellowness). Hue (H°) and chroma (C^*) [33] were calculated following Eqs. 3 and 4.

$$\text{Hue} = \tan^{-1}(b/a) \quad (3)$$

$$\text{Chroma} = \sqrt{(a^2 + b^2)} \quad (4)$$

Measurement of tomato firmness

The firmness of pressure-treated tomatoes was measured using a texture analyzer (TA.XTExpress, Stable Micro Systems Ltd., Godalming, UK) according to a described procedure [21]. Maximum force (g) was used as an index of firmness. Tomatoes were compressed to 30% deformation in a single compression-decompression cycle at a steady speed of $5\ \text{mm min}^{-1}$ using a 50 mm diameter circular flat plate. Ten different tomato samples were used and 3 readings were taken for each fruit. Texture Expert software (Version 1.1.12.0) was used to measure the maximum force.

Statistical analysis

Data obtained from triplicate determinations were analyzed using the one-way analysis of variance (ANOVA) function of the Statistical Package for the Social Sciences (SPSS version 21, IBM Corporation, USA) and expressed as mean values $\pm$ standard deviation. The Student–Newman–Keuls test was applied at a confidence level of $p < 0.05$.

Results and discussion

Inactivation of *Salmonella* Typhimurium

The disinfection efficiency of UV, UVT, and chlorine treatments against *Salmonella* Typhimurium is shown in Fig. 2. The initial average population of *Salmonella* Typhimurium on fruit surfaces was $5.47\ \log\ \text{CFU/mL}$. UV treatments for 5, 10, and 15 min resulted in bacterial count decreases of 0.48, 0.65, and 1.01 log, respectively. UVT treatments for 5, 10, and 15 min resulted in bacterial count decreases of 0.63, 0.92, and 2.19 log, respectively. Chlorine disinfection caused relatively greater bacterial count reductions of 1.34, 1.56, and 1.91 log for 5, 10, and 15 min treatments, respectively. UVT was found to be significantly more effective than UV after 10 min of treatment. Chlorine disinfection was more effective than UVT for 10 min; however, after 14 min of treatment, UVT caused

Fig. 2 Effects of single treatments for inactivation of *Salmonella* Typhimurium inoculated onto cherry tomato surfaces. $N_0 = 5.47$ log CFU/mL. Error bars represent mean $\pm$ standard deviation ($n = 3$). Control (open circle), UV (green open triangle), UVT (blue filled triangle), and chlorine disinfection (red filled diamond). (Color figure online)

significantly greater reductions in bacterial counts than chlorine (Fig. 2). Chlorine concentrations varying between 50 and 200 ppm for 5 min are commonly applied during disinfection of fresh produce [22]. In our study, the highest chlorine concentration of 200 ppm was used that showed less efficiency than UVT after 14 min of treatment. A sequential combination of UVT or chlorine treatments with HHP showed significantly greater inactivation efficacies than single treatments (Fig. 3). A maximum bacterial count reduction of 5.47 log, to below the detection limit, was achieved when a UVT for 15 min or chlorine for 15 min was combined with HHP at 500 MPa for 1 min. A combination of UVT with HHP is, however, a more promising alternative to keep chlorine out of the fresh produce disinfection process as proposed in this study.

Fig. 3 Effects of combined treatments for inactivation of *Salmonella* Typhimurium inoculated onto cherry tomato surfaces. $N_0 = 5.47$ log CFU/mL. Error bars represent mean $\pm$ standard deviation ($n = 3$). HHP (open square), Chlorine-HHP (shaded filled square), and UVT-HHP (filled square)

The frequency of reported foodborne diseases linked to fresh produce has increased in recent decades. Fresh fruit can become contaminated with pathogenic microorganisms during production, harvest, post-harvest handling, and distribution [5, 22]. Chlorine-based disinfectants are the most widely used methods for sanitization of fresh produce surfaces against pathogenic microorganisms at commercial scales. Application of chlorine-based disinfectants is; however, considered to be responsible for numerous health and environment risks. Hypochlorous acid can rapidly react with organic matter in water, leading to formation of trihalomethanes, haloketones, haloacetic acids, and chloropicrin by-products that can remain on final product surfaces. Trihalomethanes are carcinogenic compounds considered to be responsible for cancers. Prolonged exposure to chlorine vapors can cause irritation of skin and occupational health concerns have been raised [5, 6, 22, 23].

UV processing is a promising alternative method to conventional chlorine disinfection of fresh produce, but has limitations. The shadowing effect has limited the industrial applications of UV disinfection for fresh fruits. Microorganisms attached to rough food surfaces or present in crevices are hard to target using UV light [7]. Target microorganisms present on food surfaces must directly face a UV lamp to be inactivated. Moreover, when UV light is commercially applied to fresh fruit in a processing line, all parts of fruits are not directly exposed to UV light as fruit would be rolling on a conveyor belt [24]. In the past decade, research into UV processing has focused on hurdle approaches to achieve higher microbial reduction levels [4, 7–9, 15, 23, 25]. Equipment engineering approaches have also been used to overcome limitations of UV processing. A water-assisted UV system was introduced by Liu et al. [23] for microbial inactivation on fresh blueberries in both small and large scale experiments. In our study, a water-assisted UVT reactor with turbulent flow was developed to overcome the UV limitation of the shadowing effect. An air pump was fitted at the bottom of the reactor to create turbulent flow with rotation of fruits for uniform disinfection of surfaces (Fig. 1).

Photo-killing effects of TiO_2 on bacteria in liquid cultures have been widely studied [8, 11]. Crystals of a semiconductor material, such as titanium dioxide (TiO_2), are polarized upon exposure to UV light, causing active oxidation–reduction reactions that lead to formation of highly oxidized hydroxyl radicals (OH radical) via oxidative decomposition of water molecules. The hydroxyl radicals degrade microorganisms to the extent that they lose the ability of photoreactivation [26, 27]. The U.S. FDA has approved use of TiO_2 as an additive in human foods, drugs, cosmetics, and food contact materials [28]. A UVT process can be easily incorporated into existing UV

light operations. TiO_2 photocatalytic reaction under UV light is more effective for microbial inactivation than simple UV light. In recent years, UVT technology has been reported to overcome limitations of simple UV for disinfection of fresh produce to a better degree than chlorine disinfection [8, 11–13].

Combination treatments are becoming increasingly popular for enhanced microbial inactivation via synergistic effects. Combination of nonthermal technologies allows use of lower individual treatment intensities for reduction of negative processing effects on nutritive values and freshness of foods [15, 16, 25]. Results of our study showed that a UVT–HHP combined treatment was more effective for bacterial disinfection of tomato surfaces than single treatments. In another study, ultrasound in conjunction with peracetic acid resulted in reductions of *Salmonella* counts on cherry tomato surfaces [29], suggesting that a combined treatment was an effective alternative disinfection process that did not create toxic residues on fruit surfaces, similar to results reported herein. Synergistic inactivation of microorganisms in a sequential combined treatment is probably due to multiple damage mechanisms caused by different inactivation treatments, resulting in multiple injury types to cell structures [16, 25].

Changes in nutritional values, color, and firmness of cherry tomatoes

Tomatoes are rich in lycopene (71.6%), beta-carotene (17.2%), vitamin C (12%), dietary antioxidants, and phenolics [30, 31]. Phenolic and antioxidant compounds of tomato fruit are considered to prevent different types of

cancers and cardiovascular diseases [17, 31]. The nutritive value of tomato products is an important consumer concern considering effects of processing and storage [32]. Changes in lycopene, ascorbic acid, and total phenolic contents, and DPPH radical scavenging activities in tomatoes after different inactivation treatments are shown in Table 1. Lycopene contents did not show significant ($p > 0.05$) changes after any inactivation treatment, compared with controls. Minor changes were observed in total phenolic contents and antioxidant activities of tomatoes. Ascorbic acid contents were significantly ($p < 0.05$) decreased after all treatments, compared with controls (Table 1). Surface color parameter values of tomatoes are shown in Table 2. The red value (a^*) was significantly ($p < 0.05$) reduced only for low pressure treated tomatoes at 300 MPa, compared with all other treatments. Conversely, yellowness (b^*) and luminosity (L^*) values were not significantly ($p < 0.05$) changed under any treatment conditions. Hue is the degree to which a color can be described as similar to or different from red, green, blue, and yellow. Chroma is color relative to the brightness of another color that appears white under similar viewing conditions [33]. Hue (H) and chroma (C^*) values remained unchanged after combined treatments. The cherry tomato color, thus, remained unaffected after the UVT–HHP combined treatment (Table 2). Cherry tomatoes showed a softer texture after HHP treatment than control fruit that is one limitation of the study (Fig. 4).

The characteristic red color of ripe tomatoes is mainly due to the presence of the natural pigment lycopene. Lycopene degradation has a further direct impact on sensory qualities and potential health benefits of tomato-based

Table 1 Changes in nutrient quality of cherry tomatoes after different inactivation treatments

Treatment	Lycopene (mg/1000 g fw)	Ascorbic acid (mg/100 g fw)	Total phenolics (mg GAE/g dw)	DPPH activity (%)
Control	31.90 $\pm$ 0.63 ^a	34.05 $\pm$ 3.74 ^a	49.84 $\pm$ 0.01 ^a	95.32 $\pm$ 0.70 ^a
Chlorine	30.37 $\pm$ 1.31 ^a	29.53 $\pm$ 3.06 ^{ab}	49.80 $\pm$ 0.06 ^a	95.75 $\pm$ 0.61 ^a
UV	30.85 $\pm$ 1.48 ^a	30.62 $\pm$ 3.80 ^{ab}	49.79 $\pm$ 0.09 ^a	95.81 $\pm$ 0.76 ^a
UVT	30.68 $\pm$ 0.40 ^a	28.17 $\pm$ 2.49 ^{ab}	49.78 $\pm$ 0.11 ^a	96.07 $\pm$ 0.23 ^a
HHP 300 MPa	29.58 $\pm$ 1.11 ^a	21.97 $\pm$ 3.72 ^b	49.81 $\pm$ 0.15 ^a	96.17 $\pm$ 0.52 ^a
HHP 400 MPa	30.08 $\pm$ 0.88 ^a	22.38 $\pm$ 4.70 ^b	49.77 $\pm$ 0.11 ^a	95.72 $\pm$ 1.13 ^a
HHP 500 MPa	30.84 $\pm$ 1.56 ^a	23.04 $\pm$ 3.92 ^b	49.86 $\pm$ 0.02 ^a	95.79 $\pm$ 0.14 ^a
Chlorine–HHP300	30.10 $\pm$ 0.90 ^a	21.26 $\pm$ 2.94 ^b	49.82 $\pm$ 0.14 ^a	96.28 $\pm$ 0.34 ^a
Chlorine–HHP400	30.21 $\pm$ 0.65 ^a	21.70 $\pm$ 1.88 ^b	49.88 $\pm$ 0.12 ^a	95.95 $\pm$ 0.33 ^a
Chlorine–HHP500	30.55 $\pm$ 1.07 ^a	21.18 $\pm$ 3.87 ^b	49.86 $\pm$ 0.12 ^a	96.50 $\pm$ 0.09 ^a
UVT–HHP300	29.86 $\pm$ 0.62 ^a	21.05 $\pm$ 4.03 ^b	49.81 $\pm$ 0.21 ^a	96.12 $\pm$ 0.17 ^a
UVT–HHP400	30.04 $\pm$ 1.51 ^a	22.09 $\pm$ 4.05 ^b	49.81 $\pm$ 0.06 ^a	96.40 $\pm$ 0.17 ^a
UVT–HHP500	29.72 $\pm$ 0.87 ^a	21.21 $\pm$ 2.90 ^b	49.89 $\pm$ 0.11 ^a	95.82 $\pm$ 0.79 ^a

Values are expressed as mean $\pm$ standard deviation ($n = 3$)

Different lower case letters in the same column for each treatment correspond to significant differences at $p < 0.05$

Table 2 Changes in the surface color of cherry tomatoes after different inactivation treatments

Treatment	L* Lightness	a* Redness	b* Yellowness	H° Hue	C* Chroma
Control	38.2 ± 1.3 ^a	18.7 ± 2.0 ^a	20.2 ± 1.9 ^{ab}	47.3 ± 1.4 ^b	27.5 ± 2.7 ^{ab}
Chlorine	38.8 ± 1.2 ^a	18.6 ± 1.4 ^a	19.8 ± 2.4 ^{ab}	46.8 ± 1.5 ^b	27.2 ± 2.7 ^{ab}
UV	38.0 ± 1.2 ^a	18.4 ± 0.7 ^a	19.2 ± 1.0 ^b	46.2 ± 2.1 ^b	26.6 ± 0.7 ^{ab}
UVT	38.3 ± 1.1 ^a	18.5 ± 1.1 ^a	19.1 ± 2.4 ^b	45.8 ± 2.5 ^b	26.5 ± 2.4 ^{ab}
HHP 300 MPa	36.6 ± 4.7 ^a	12.3 ± 1.3 ^d	20.8 ± 1.7 ^{ab}	59.3 ± 4.4 ^a	24.2 ± 1.0 ^b
HHP 400 MPa	40.7 ± 0.9 ^a	15.9 ± 1.9 ^{abc}	22.7 ± 0.9 ^{ab}	55.2 ± 4.0 ^a	27.8 ± 0.9 ^{ab}
HHP 500 MPa	40.6 ± 0.5 ^a	18.4 ± 1.0 ^a	23.7 ± 0.2 ^{ab}	52.2 ± 1.4 ^{ab}	30.0 ± 0.7 ^a
Chlorine–HHP300	37.6 ± 0.4 ^a	13.3 ± 0.9 ^{cd}	19.6 ± 0.4 ^{ab}	55.9 ± 1.2 ^a	23.7 ± 0.8 ^b
Chlorine–HHP400	39.6 ± 1.7 ^a	15.6 ± 2.2 ^{abc}	22.6 ± 1.0 ^{ab}	55.5 ± 3.7 ^a	27.5 ± 1.7 ^{ab}
Chlorine–HHP500	38.8 ± 2.9 ^a	18.9 ± 0.1 ^a	24.3 ± 3.0 ^a	51.9 ± 3.7 ^{ab}	30.8 ± 2.3 ^a
UVT–HHP300	36.8 ± 3.7 ^a	13.7 ± 1.0 ^{bcd}	20.5 ± 1.7 ^{ab}	56.1 ± 4.2 ^a	24.7 ± 0.9 ^b
UVT–HHP400	39.7 ± 1.1 ^a	17.0 ± 2.3 ^{ab}	22.6 ± 1.7 ^{ab}	53.2 ± 4.9 ^{ab}	28.3 ± 1.6 ^{ab}
UVT–HHP500	40.4 ± 0.5 ^a	19.1 ± 1.8 ^a	24.2 ± 0.7 ^a	51.8 ± 2.0 ^{ab}	30.9 ± 1.6 ^a

Values are expressed as mean ± standard deviation ($n = 3$)

Different lower case letters in the same column for each treatment correspond to significant differences at $p < 0.05$

Fig. 4 Changes in firmness of cherry tomatoes after HHP treatment compared with control. Error bars are expressed as mean ± standard deviation ($n = 3$)

foods [31]. Herein, chemical quality parameters of cherry tomatoes, including lycopene and total phenolic contents, and the antioxidant activity, were slightly changed without a significant difference after any treatment, compared with controls. Bravo et al. [34] found that the lycopene and total phenolic contents, and the antioxidant capacity in breaker tomatoes were increased after UV during storage at room temperature. Qiu et al. [35] reported that HHP is a potential method for producing ambient-stable tomato products for lycopene preservation. Tomato puree treated with HHP 500 MPa for 12 min appeared to be stable for lycopene during storage at refrigerated temperatures for about 6 months. In our study, lycopene contents of cherry tomatoes were slightly increased immediately after simple UV.

Fruit softness or loss of firmness occurs as a result of deterioration in cell wall structures and changes in cellulose and pectin components [30]. Tomato firmness generally decreases during postharvest storage due to softness of fruit tissues via metabolic changes induced by enzymatic action and respiration [4]. In our study, a decrease in firmness of tomatoes was obvious after HHP treatments compared with control tomatoes (Fig. 4). Low pressure levels of 300–400 MPa caused more softness than relatively high pressure level of 500 MPa. This might be because softening enzymes remained active at low pressure levels. A correlation between HHP treatment and texture of cherry tomatoes was reported by Tangwongchai et al. [21] where softness of fruits might have been caused by key softening enzymes such as pectinmethylesterase (PME) and polygalacturonase (PG). Guerreiro et al. [3] also observed a decrease in firmness of cherry tomatoes after irradiation, compared with non-irradiated fruit.

In summary, pre-washing of cherry tomatoes in UVT water-assisted system for 15 min followed by post-package HHP treatment at 500 MPa for 1 min led to a synergistic effect against *Salmonella* Typhimurium on cherry tomatoes, resulting in a maximum 5.47 log reduction while keeping the individual treatment intensities at low-level. Turbulent flow in water created by the air pump fitted at the bottom of a UVT reactor helped in rotation of fruits for uniform disinfection during processing. UVT–HHP combination treatment showed potential for decontamination of *Salmonella* Typhimurium on cherry tomatoes without affecting nutritional quality for production of RTE cherry tomatoes and other similar fruits for fresh markets. The limitation of HPP post-package treatment is the softness in

tomatoes. The present study provides a safe and effective post-harvest intervention strategy for the fresh produce industry as an alternative to chlorine based washing.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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