Application of Ultraviolet-C Light on Storage Rots and Ripening of Tomatoes

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ABSTRACT

The application of ultraviolet light (UV-C, 254 nm) hormesis on fruits and vegetables to stimulate beneficial responses is a new method for controlling storage rots and extending the shelf-life of fruits and vegetables. The present study was aimed at treating tomatoes (Lycopersicon esculentum) with different UV-C dosages (1.3 to 40 KJ/m²) to induce resistance to black mold (Alternaria alternata), gray mold (Botrytis cinerea), and Rhizopus soft rot (Rhizopus stolonifer). These diseases were effectively reduced when tomatoes were inoculated following UV-C irradiation. UV-C treated tomatoes were firmer in texture and less red in color than the control tomatoes, indicating a delay in ripening. Slower ripening and resistance to storage rots of tomatoes are probably related. The positive effect of UV-C on tomatoes decreased as treatments were performed at stages of increased ripeness.

Major postharvest diseases of tomatoes (Lycopersicon esculentum Mill.) include black mold caused by Alternaria alternata (Fr. Keissler), Rhizopus soft rot caused by Rhizopus stolonifer (Ehrenb. ex Fr.) and gray mold caused by Botrytis cinerea (Pers. ex Fr.) (13). Preharvest field applications of protective fungicides are used about 7 weeks before harvest for reducing fungal contamination and subsequently reducing postharvest storage rots of fresh market tomatoes. However, fungicides are being removed from the market due to mounting concerns about health risks associated with them and imposed bans by the U.S. Environmental Protection Agency. In some instances fungicides have been voluntarily removed because the anticipated profits are not high enough to justify the cost of re-registration with the Environmental Protection Agency (8). Clearly, there is an urgent need for an alternative management practice to fungicide application for postharvest disease control of fresh market tomatoes.

Field-grown tomatoes may dramatically lose resistance to black mold due to low temperature stress, chilling injury, or exposure to high temperature. A. alternata is believed to produce latent infection in developing tomatoes (13). Thus, resistance to black mold can be lost without the appearance of obvious physiological symptoms of injury from low or high temperature stress (12,13). In addition, preharvest chilling was found to decrease tolerance of tomato fruit to bacterial soft rot (12). Therefore, a method to reduce these losses is needed.

For long-distance shipping, tomatoes must be harvested at the mature-green stage, then ripened either in transit or in ripening rooms at final destination (9). However, too rapid ripening is not desirable. As demand increases, fruit and vegetable growers continue to search for ways to raise and market products which can withstand lengthy delays and the damaging conditions of the shipping process, such as mechanical failure of the environmental control devices utilized in shipping vehicles, storage and display facilities, and simple power failure. A need therefore exists for a safe, acceptable method for delaying the ripening and reducing storage rots of fresh produce.

A relatively recent concept of ultraviolet light (UV-C, 254 nm) hormesis (7) was shown to induce resistance in fruits and vegetables to postharvest storage rots (5,15,16) and extended the shelf life of fruits by delaying the ripening process (6). The results of these findings represented the first approach to crop protection for the control of postharvest diseases by using UV-C light. Luckey (7) defined hormesis as a stimulation of a beneficial plant response by low doses of an agent such as a chemical inhibitor or physical stressor. Hormetin is the agent that is stimulatory in subharmful doses such as UV radiation, while hormetic is the adjective of hormetin.

The objectives of this study were: i) to determine the hormetic effect of low dose UV-C light on induced resistance of tomatoes to postharvest storage rots; ii) to evaluate the effect of UV-C light on the ripening of tomatoes; and iii) to study the effect of delayed ripening associated with UV-C treatment on induced resistance of tomato fruits to storage rots.

MATERIALS AND METHODS

Tomatoes

Tuskegee 80-130 and Floradade tomatoes were harvested from greenhouse and field plots at the George Washington Carver
Agricultural Experiment Station and Better Boy was harvested from a field plot at E. V. Smith Research Center of the Alabama Experiment Station at Milstead, AL. All fruits used in this study were selected for uniformity in size and freedom from visible injuries. Tomatoes were treated with UV-C within 24 h after harvest. In each experiment, 20 fruits per treatment were inoculated, and for the evaluation of natural infected black mold and bacteria soft rot of tomatoes, 10-15 fruits per treatment were replicated three times.

The maturity stages of tomato are described as color changes in the exocarp according to Salunkhe and Desai (11) and Rick (9). The stages are mature green (stage 1), breaker (stage 2), orange color (stage 3), red color (stage 4), and red-ripe color (stage 5). The percent ripeness is presented as the percentage of tomatoes at stage 3 to stage 5. When studying the effect of UV-C on ripening, tomatoes were harvested at the green maturity stage (stage 1). After 11 d, UV-C treated tomatoes were sorted into five stages of maturity by visually counting and expressed as percent ripeness.

**Ultraviolet irradiation**

Fruits were randomly assigned to each treatment which consisted of a control and different doses of UV-C ranging from 1.3 to 40 KJ/m². A quasi-monochromatic UV radiation at 254 nm was obtained from a high intensity General Electric (G.E.) low-pressure mercury-vapor discharge germicidal lamp. Approximately 95% of the total UV emission of the lamp was at 254 nm. This information was calculated from data obtained from G.E. and reported by Harm (3). G.E. lamp (G30T8), with a nominal power output of 30 watts and amperage of 0-3.6, was used to irradiate tomatoes. The lamp had a tube diameter of 2.5 cm and a length of 88 cm. About 35 to 40 KJ/m² was applied to the fruit surface. Each UV-C treatment dose was divided into 4 smaller subdoses, and each fruit was individually rotated four times exposing four separate sides of each fruit to the lamp. Exposure time at each rotation of the fruit was measured by a timer connected with the UV lamp. All fruits were also randomly moved to four different positions within the UV-C field which averaged 1.28 mW/cm². A digital radiometer (Ultraviolet Products, Inc. San Gabriel, CA) was used to measure UV-C irradiation. UV-C irradiation exposure times were 1.75 min for 1.3 KJ/m², 3.23 min for 2.4 KJ/m², 4.83 min for 3.6 KJ/m², 6.45 min for 4.8 KJ/m², 10.10 min for 7.5 KJ/m², 26.9 min for 20 KJ/m², and 53.76 min for 40 KJ/m². Following UV-C irradiation, fruits were separated into small lots, placed in paper bags, and stored in the dark at room temperature and 52% relative humidity.

Examination of naturally infected fruits

In the 1990 test, UV-C treated and nontreated tomatoes were kept at 24°C for 10 d. Tomatoes were examined daily and fruits showing natural black mold and bacterial soft rot infection were removed and the number of rotts counted. The causative organisms were isolated on potato dextrose agar (PDA) and identified (1).

External color and firmness

The color of tomatoes, expressed as ‘L’ (whiteness), ‘a’ (redness), and ‘b’ (yellowness), was measured using a Minolta-Chroma Meltler II (Minolta Camera Co., LTD Ramsey, NJ). Three measurements were taken on each of 12 fruits, and also, 7 d after UV-C treatment the results were expressed as ‘ab’ ratios.

Firmness was determined by the procedure described by Lu et al. (6). Twenty tomatoes from each treatment were randomly tested. Two different sides of each fruit were tested for firmness with an Instron 1132 texture meter (Instron Corp., Canton, MA) equipped with a Magness-Taylor probe to penetrate 1.5 cm deep and the measurements were expressed (puncture resistance) in Kg.

Inoculation study

In the 1991 test, tomatoes were inoculated with storage rot fungi. In the first inoculation experiment, tomatoes harvested at the breaker and mature-green stages of maturity were inoculated with R. stolonifer and B. cinerea 4 d after UV-C treatment. Tomatoes inoculated with A. alternata were stored for 10 d at 4°C before inoculation. In the second experiment, tomatoes were inoculated with R. stolonifer 5 d after UV-C treatment at the green-maturity, breaker, and red-color stages. In the third experiment, tomatoes were harvested at green maturity and allowed to ripen to the four maturity groups, then inoculated with R. stolonifer and B. cinerea 9 d after UV-C treatment.

All storage rot fungi were maintained on acidified PDA. To obtain inocula, all fungi were grown on PDA for 6-10 d at 25°C. Spore suspensions were prepared by washing the colonies with 5 ml of sterile water containing 0.03% Tween 80 (1,18). Aliquots were collected and diluted to the desired concentration as determined by a hemacytometer. Four to nine days after UV-C treatment the surface of all fruits were sterilized with 95% alcohol, and two wounds per fruit were made with a dissecting needle to a depth of 3 mm. Twenty microliters of a conidial suspension containing 10⁵ conidia per ml was applied to each wound as described previously (18). Also included were tomatoes that were surface sterilized and wounded but were not inoculated.

Inoculated fruits were incubated in plastic bags with moist filter paper for 1-2 d at 24°C. Following inoculation with spore suspensions of fungi, decay around wounds occurred within 15-48 h depending on the fungus. The percent infection was determined by assessing the number of infected wounds out of the total number of wounds. Lesion diameter was determined 24 to 48 h for Rhizopus soft rot and gray mold following inoculation. Each treatment consisted of 20 fruits for a total of 40 inoculation sites per treatment.

Statistical analysis

All experiments were conducted in a randomized block design and percentage data transformed using values from a standardize arcsin percentage transformation table, to stabilize variances before analysis, however all data are reported as the actual percentages. The data were then subjected to 1st and 2nd degree polynomial analysis where appropriate (14).

**RESULTS AND DISCUSSION**

Prior to the tomato harvest in 1990 the field temperature was about 15°C for one week and fruits were possibly subjected to chilling injuries. Also tomatoes may have been subjected to high temperature stress as the temperature was 31°C at harvest and black mold was present. It was reported that chilling injuries or high temperature stress decreased resistance of tomatoes to black mold and bacterial soft rot (12). The application of low dose UV-C of 7.5 KJ/m² to tomatoes in mature-green and breaker stages of maturity reduced black mold and bacterial soft rot (Erwinia spp.) of naturally infected fruits. The regression analysis at the breaker stage shows a quadratic effect of the UV-C dose for blackrot reduction. The percent decay of tomatoes treated with UV-C dose of 7.5 KJ/m² was 29 and that of the control was 85%. However, breaker tomatoes treated with 40 KJ/m² had 77% black mold and bacterial soft rot (Table 1). The percent decay at the green stage of maturity in both UV-C and nontreated fruits was significantly lower than those harvested at the breaker stage (Table 1). The results in Table 1 further show that UV-C treated fruits harvested at the green stage of maturity (4.8 KJ/m²) showed no decay 10 d after irradiation, while 16% of the control fruits decayed.
The effect of UV-C light on the percent decay of fruits naturally infected black mold and bacterial soft rot of Tuskegee 80-130 tomatoes irradiated at breaker and green stages of maturity.

<table>
<thead>
<tr>
<th>UV-C level KJ/m²</th>
<th>Days after treatment</th>
<th>Decay (%)</th>
<th>Black mold</th>
<th>Bacterial soft rot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaker stage</td>
<td>5°</td>
<td>10°</td>
<td>5°</td>
<td>10°</td>
</tr>
<tr>
<td>0</td>
<td>44</td>
<td>85</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>1.3</td>
<td>30</td>
<td>70</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>2.4</td>
<td>29</td>
<td>68</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>3.6</td>
<td>9</td>
<td>49</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>4.8</td>
<td>5</td>
<td>39</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7.5</td>
<td>8</td>
<td>29</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>20.0</td>
<td>7</td>
<td>56</td>
<td>3</td>
<td>53</td>
</tr>
<tr>
<td>27.0</td>
<td>12</td>
<td>61</td>
<td>21</td>
<td>61</td>
</tr>
<tr>
<td>40.0</td>
<td>30</td>
<td>77</td>
<td>11</td>
<td>77</td>
</tr>
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</table>

Quadratic regression equation of UV-C doses (x) on percent decay of tomatoes (y), r² and regression coefficient values are as follows:

\[ y = 30.51 - 2.96x + 0.076x^2, r^2 = 0.97 \text{ and significant at } P < 0.001 \]

The effect of UV-C on decay development of tomatoes inoculated with storage rot fungi was investigated in 1991. Also, a quadratic effect of UV-C on the reduction of the incidence of decay and lesion size for black and gray molds and Rhizopus soft rot was observed at the optimum doses of 7.5, 7.5, and 3.6 KJ/m², respectively (Table 2). Stevens et al. (16) reported that decay development was small (or subdued) in the inoculated fruits which were previously treated with UV-C.

The first inoculation experiment percent decay of black mold were determined at 48 h after inoculation. The percent of decay and lesion diameter of gray mold and Rhizopus soft rot were determined at 24 h after inoculation. The percent of decay and lesion diameter of Rhizopus rot were determined at 15 and 23 h after inoculation, respectively.

Quadratic regression equation of UV-C doses (x) on percent decay of tomatoes (y), r² and regression coefficient values are as follows:

\[ y = 38.38 + 1.67x + 0.03x^2, r^2 = 0.25 \text{ and not significant} \]

<table>
<thead>
<tr>
<th>UV-C levels KJ/m²</th>
<th>Tomatoes at different ripening stages (%)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
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<tr>
<td>0</td>
<td>0</td>
<td>37</td>
<td>16</td>
<td>16</td>
<td>31</td>
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</tr>
<tr>
<td>1.3</td>
<td>40</td>
<td>25</td>
<td>15</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.4</td>
<td>49</td>
<td>26</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3.6</td>
<td>37</td>
<td>47</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4.8</td>
<td>67</td>
<td>19</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7.5</td>
<td>54</td>
<td>32</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20.0</td>
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<td>25</td>
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<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>40.0</td>
<td>71</td>
<td>29</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Results of the UV-C effect on tomato ripening are shown in Table 3 and Fig. 1. The application of UV-C on tomatoes harvested in 1990 and 1991 delayed ripening, as indicated by a decrease in the percent ripening of tomatoes (percentage of tomatoes in the orange to ripe-red color stages). Tomatoes treated with UV-C doses of 3.6 and 4.8 KJ/m² resulted in slower color changes of the exocarp from green to red compared to other dosages (Fig. 1). Fruit ripening is accompanied by changes in fruit tissue physiology as color changes in the exocarp from green to red. Degreening of the tissue is caused mainly by chlorophyll loss during ripening (2,9,11). The application of UV-C to tomatoes delayed the ripening process and the production of pigments such as lycopene (red) and beta-carotene (orange) (2,9,11). Furthermore, as
Figure 1. The effect of UV-C on delaying ripening of Better Boy, Tuskegee 80-130, and Floradade tomatoes. Quadratic regression equation of UV-C doses (x) on percent ripening of tomatoes (y), \( r^2 \) and regression coefficient values are as follow: Better Boy, \( y = 24.25 - 4.38x + 0.22x^2, r^2 = 0.97 \) and significant at \( P < 0.001 \); Tuskegee 80-130, \( y = 34.71 + 4.83x - 0.24x^2, r^2 = 0.98 \) and significant at \( P < 0.001 \) and Floradade, \( y = 77 - 4.08x + 0.15x^2, r^2 = 0.92 \) and significant at \( P < 0.001 \).

The effect of UV-C on color values of 'a', 'L', 'b' and a/b ratio of the outer exocarp of Tuskegee 80-130 tomatoes.

<table>
<thead>
<tr>
<th>UV-C levels (KJ/m²)</th>
<th>'a' (°)</th>
<th>'L'</th>
<th>'b'</th>
<th>'a/b' ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15.7</td>
<td>52.7</td>
<td>26.1</td>
<td>0.78</td>
</tr>
<tr>
<td>1.3</td>
<td>5.2</td>
<td>57.4</td>
<td>21.1</td>
<td>0.25</td>
</tr>
<tr>
<td>2.4</td>
<td>4.7</td>
<td>59.3</td>
<td>21.0</td>
<td>0.24</td>
</tr>
<tr>
<td>3.6</td>
<td>5.6</td>
<td>57.7</td>
<td>20.6</td>
<td>0.30</td>
</tr>
<tr>
<td>4.8</td>
<td>9.8</td>
<td>52.2</td>
<td>18.9</td>
<td>0.52</td>
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<tr>
<td>7.5</td>
<td>9.1</td>
<td>55.2</td>
<td>20.4</td>
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<tr>
<td>20.0</td>
<td>6.2</td>
<td>56.3</td>
<td>20.4</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Quadratic regression equation of UV-C doses (x) on 'a', 'L', 'b' and a/b ratio of tomatoes (y), \( r^2 \) and regression coefficient values are as follows:

\( y = 9.90 - 0.61x + 0.02x^2, r^2 = 0.92 \) and significant at \( P < 0.001 \)
\( y = 56.43 - 0.22x + 0.01x^2, r^2 = 0.94 \) and significant at \( P < 0.001 \)
\( y = 24.57 - 1.2x + 0.05x^2, r^2 = 0.89 \) and significant at \( P < 0.001 \)

Low values of a/b indicate greener fruit while high values indicate more red fruits. The color values were determined seven days after UV-C treatment.

Low dosages of UV-C delayed ripening, higher dosages (20 to 40 KJ/m²) resulted in the development of an undesirable discoloration of the exocarps (no data shown). The skin color of tomato changes to red with ripening; therefore, measuring the color values especially the red color serves as the best indicator related to the ripening of tomato. Table 4 shows the 'L', 'a', 'b', and 'a/b' ratio values as affected by varying doses of UV-C. The 'a' value which is related to red color was the highest for the control while it was smaller for tomatoes treated with UV-C doses of 1.3 to 3.6 and 20 KJ/m². The 'b' value which is related to yellowness was also higher for control than UV-C treated tomatoes. However, the 'L' value which is related to lightness varied among treatments. The low 'a/b' of UV-C treated fruits as compared to control fruit indicated that UV-C treated tomatoes were greener. The result of 'a', 'b', and 'a/b' ratio values agreed with visual observation in that tomatoes treated with UV-C delay ripening.

Results of flesh firmness of tomatoes are shown in Table 5. Firmness for all treatments decreased as maturity increased. However, regression analyses of results of fruits treated with UV-C (2.4 to 20 KJ/m²) at stage 1 of maturity were significantly firmer than control fruits. Softening in ripe tomatoes is attributed to solubilization of pectin resulting from polygalacturonase activity. Fruits exhibiting advanced maturity associated with reduction in firmness resulted in a greater susceptibility of tomatoes to storage rot (9,11).

Results of UV-C treatment of tomatoes of different maturity groups inoculated with fungi are shown in Table 6.
Figure 2. The effect of UV-C on gray mold at different ripening stages of Tuskegee 80-130 tomatoes in the third inoculation test. Quadratic regression equation of UV-C doses (x) on percent decay of tomatoes at different ripening stages (y), $r^2$ and regression coefficient values are as follow: Stage 1: There was no relationship; Stage 2, $y = 79 - 11.42x + 0.42x^2$, $r^2 = 0.97$ and significant at $P \leq 0.001$; Stage 3, $y = 98 - 12.49x + 0.56x^2$, $r^2 = 0.98$ and significant at $P \leq 0.001$ and Stage 4, $y = 58.86 + 12.61x - 0.63x^2$, $r^2 = 0.17$ and is not significant.

Figure 3. The effect of UV-C on Rhizopus soft rot at different stages of ripening of Tuskegee 80-130 tomatoes in the third inoculation test. Quadratic regression equation of UV-C doses (x) on percent decay of tomatoes at different ripening stages (y), $r^2$ and regression coefficient values are as follow: Stage 1, $y = 98.85 - 16.68x - 0.82x^2$, $r^2 = 0.97$ and significant at $P \leq 0.001$; Stage 2, $y = 99.29 - 2.13x + 0.11x^2$, $r^2 = 0.97$ and significant at $P \leq 0.001$; Stage 3 and 4, $y = 100\%$ rot for all dose levels.

The induced resistance response of fruits to UV-C treatment to Rhizopus soft rot and gray mold appears to decrease with advancing stages of ripening. The percent decay and lesion size of UV-C treated tomatoes at green-maturity and breaker stages were significantly smaller compared to fruits treated at the orange to red stage of maturity. In fact, when red tomatoes were inoculated with *R. stolonifer*, the percent decay and lesion size observed 24 h after inoculation showed no significant difference between UV-C treatments and the nontreated control (Table 6 and Fig. 3). Recently, Lu et al. (6) reported that UV-C treatment of apples and peaches delayed ripening and found that increased resistance to decay and delayed ripening appears to be closely related. Thus, reduced storage rot could be a secondary effect of delayed maturation. The delay in ripening of host tissue could also delay the reduction of substances inhibitory to storage rot pathogens. It is known that tomato fruits contain glycosidic steroidal compounds, tomatine. Kajderowicz-Jarosinska (4) found that tomatine decreases as tomatoes ripen. Green tomatoes contain 0.09% tomatine which is reduced to about half in yellowish fruits and to almost 0% in red-ripe tomatoes. Tomatine is known to be toxic to some fungi (10). Verhoeft and Liem (17) reported that tomatine restricted the development of *B. cinerea* in tomato fruits by strongly inhibiting mycelial growth.

Results of our study as indicated above showed no negative correlation between UV-C dosages versus induced storage rot resistance. However, depending on the stage of maturity, a UV-C hormetic dose-response quadratic relationship was observed in disease development (Tables 1, 2, 6 and Fig. 2 and 3). This was characterized by V-shaped dose-response curves of UV-C dosages versus storage rot development with an UV-C optimum dose (s) occurring at an intermediate level. Luckey (7) reported that radiation hormesis in plants increases physiological processes such as respiration, seed germination, growth and development, and resistances to diseases. Conversely, Luckey (7) indicated that higher dosages of a stress such as radiation decreased physiological performance and death of living organisms. Application of higher UV-C dosages on tomatoes caused noticeable dull skin blemishes and increased the susceptibility of tomato fruits to storage rots (Tables 1, 2, 6 and Fig. 2 and 3).

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USE OF ULTRAVIOLET LIGHT TO CONTROL STORAGE ROTS

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