Impact of UV-C Irradiation on Quality Characteristics of Fresh-cut and Whole Plum Tomatoes

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Abstract

This study investigated the effects of three key factors, UV-C irradiation, storage time, and cutting effect, on the physicochemical properties of fresh-cut and whole plum tomatoes. UV-C irradiation was applied at three low radiation doses (0.22, 0.4 and 1.23 kJ/m^2) appropriate for the ripening stage of the tomato. Tomatoes were subsequently stored at 5.9 ^oC for four days (96 h). Mass loss analysis demonstrated significantly higher water loss in fresh-cut tomatoes (up to 12.39%) compared to whole tomatoes (max 2.65%) with UV-C treatment amplifying this effect, especially at higher UV-C doses. Colorimetric changes were more pronounced in fresh-cut samples, as indicated by the higher total colour difference (ΔE^*=6.23 vs. 2.95 in whole tomatoes) and greater chroma (C^*) reduction (11.6% vs. 4.4%) reflecting increased oxidative stress induced by tomato cutting and UV-C-exposure. Firmness decreased more in fresh-cut tomatoes (F|max reduction up to 28.5%), although UV-C irradiation moderately preserved firmness in whole fruits. Respiration rate was higher in fresh-cut tomatoes, rising by 64% in fresh-cut controls compared to whole controls (5.21 vs. 3.17mL $CO_2 \cdot kg^{-1} \cdot h^{-1}$), and was further increased by UV-C exposure (up to 7.43mL $CO_2 \cdot kg^{-1} \cdot h^{-1}$ at 1.23 kJ/m^2), indicating enhanced metabolic stress. Additionally, soluble solids and titratable acidity responded to UV-C treatment, with more pronounced changes in fresh-cut tomatoes, suggesting metabolic changes. Ethylene production increased significantly in fresh-cut tomatoes, particularly at later storage times, contributing to accelerated ripening. Overall, UV-C irradiation demonstrated potential for extending shelf-life and preserving quality in whole tomatoes by limiting water loss and maintaining firmness and colour stability. However, in fresh-cut tomatoes, the benefits were UV-C dose-dependent and limited by increased susceptibility to oxidative stress and ripening. Optimization of UV-C dosage appears necessary to balance beneficial antimicrobial and shelf-life extension effects with the minimization of quality degradation in fresh-cut products.

Keywords: UV-C; firmness; Colour; Plum tomatoes; Mass loss; Respiration rate; Ethylene production

1 Introduction

Fruits and vegetables are important in human nutrition due to their high nutritional value of bioactive compounds and significant food market presence. They are valued not only for their nutritional benefits but also for their desirable

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sensory properties, including taste, aroma, firmness, colour, gloss and freshness (Sarron et al., 2021). However, their high perishability presents significant postharvest challenges and has been associated with foodborne illness outbreaks (Denis et al., 2016). As such, effective decontamination strategies are necessary to ensure both safety and extended shelf-life. Common chemical disinfectants, such as chlorine, hydrogen peroxide and electrolyzed water, are commonly used in the fresh produce industry, with sodium hypochlorite being one of the most widely used in washing and spraying applications (Sarron et al., 2021).

While effective at reducing microbial loads and preserving product quality, growing concerns regarding the potential health and environmental impacts of synthetic additives have driven the search for safer, non-chemical alternatives (Miller et al., 2013). Ultraviolet-C (UV-C) irradiation has emerged as a promising non-thermal, residue-free technology for microbial surface decontamination of fruits and vegetables. Its germicidal effect, particularly within the 250 and 280 nm wavelength range, disrupts the functionality and integrity of microorganisms' DNA and RNA (Allende et al., 2006). Beyond microbial inactivation, UV-C irradiation has been shown to preserve the nutritional and sensory properties of produce, making it an attractive option for the treatment of minimally processed products.

The fresh-cut fruit and vegetable market has grown rapidly in the food industry, but these products are particularly susceptible to quality degradation due to increased microbial proliferation, enzymatic browning and tissue softening. Low-dose UV-C treatments have demonstrated efficacy in suppressing microbial growth on fresh-cut produce; however, further investigation is needed to understand their broader effects on quality characteristics under conditions of mechanical injury and oxidative stress (Kim et al., 2008; Mditshwa et al., 2017). Research is limited in fresh-cut tomatoes, where the impact of UV-C treatment on postharvest physiology and sensory properties remains underexplored. Additionally, the cultivar and ripening stage are known to influence tomato quality, highlighting the importance of targeted studies that account for these factors (Mditshwa et al., 2017).

This study aims to evaluate the effects of low-dose UV-C irradiation on the postharvest quality properties of plum tomatoes at the red-ripe stage, the typical maturity level for fresh consumption and ready-to-eat salads. The investigation focuses on critical physicochemical parameters, including mass loss, colour (a*/b*, h*, C*, ΔE*), firmness, respiration rate, transpiration rate, ethylene production, total soluble solids and titratable acidity. Three UV-C doses, previously identified as effective for microbial decontamination of plum tomatoes, were selected to assess their potential for maintaining quality during commercial cold storage.

2 Materials and methods

2.1 Raw material, treatments (UV-C irradiation and tomato cutting) and storage conditions

Plum tomatoes (*Solanum lycopersicum* cv. baby Roma F1) were obtained at the red ripening stage (commercial maturity) from a local cooperative in Attica, Greece. Upon arrival at the laboratory, tomatoes were rinsed with tap water for 1 min to remove dirt and soil, and the excess water was removed using kitchen roll paper. Tomatoes were then sorted into two groups: fresh-cut and whole. The fresh-cut group was prepared by longitudinally halving the tomatoes with a sterile stainless-steel knife under ambient conditions (18 ^{o}C, 80–85% RH). From these two groups, experimental samples of 60 g per sample were prepared for subsequent UV-C treatment. Three UV-C treatment levels (38 s, 60 s and 185 s) and a non-irradiated control were tested. The UV-C irradiation setup was based on the system developed by Templalexis et al. (2023). The irradiation fluence was estimated according to Keitz (1971), yielding 0.22 kJ m^{-2} (38 s), 0.40 kJ m^{-2} (60 s) and 1.23 kJ m^{-2} (185 s).

Following irradiation, all samples (both whole and fresh-cut) were stored at 5.9 ± 0.3 ^{o}C and 85.9 ± 1.8% RH for 4 days (96 days), consistent with U.S. Food and Drug U.S. Food and Drug Administration (2025) recommendations for fresh-cut tomato storage. The experimental design involved the following quality assessments during cold storage:

- **Non-destructive tests** (mass loss, colour change, respiration rate and transpiration rate): 9 samples of whole and 9 samples of fresh-cut tomatoes were assessed at 0, 24, 48, 72 and 96 h of cold storage.
- **Ethylene production rate**: 3 samples of whole and 3 samples of fresh-cut tomatoes were evaluated at 24, 72 and 96 h of cold storage.
- **Destructive tests** (texture, total soluble solids and total titratable acidity): 6 samples of whole and 6 samples of fresh-cut tomatoes were evaluated at 0 h and 96 h (3 replicates at each time point).

The chosen UV-C doses and storage conditions reflect common commercial practices for fresh-cut tomato products.

2.2 Methods for determining physico-chemical properties of tomatoes

Mass loss and transpiration rate

Tomato samples were weighed to estimate the mass loss as a percentage reduction from the initial mass. An electronic scale (PCB-440, Kern, Japan) was used with an accuracy of ±0.01 g. The mass loss (%) is given as

$$ML = 100(m_o - m_t)/m_o \quad (1)$$

where m_o and m_t are the sample mass (g) at time 0 h and at time t (h) respectively. The transpiration rate (g_w kg^{-1} h^{-1}) per initial mass is given as

$$TR_m = (1000/t)(m_o - m_t)/m_o \quad (2)$$

where t (h) is the time in which the transpiration rate estimation was carried out. According to the U.S. U.S. Department of agriculture (2024) food database, Roma tomatoes contain 2.7 g of glucose and fructose per 100 g of tomato (1.4 g of fructose and 1.3 g of glucose per 100 g of tomato). The stoichiometric equation of respiration is,

$$C_6H_{12}O_6{+}6O_2 \rightarrow 6CO_2{+}6H_2O{+}2835.3kJ \quad (3)$$

Based on the stoichiometric analogy, 2.7 g of substrate (sugar) is oxidized for every 100 g of tomato, producing A=108 $g_{water}\times(2.7\ g_{sugar}/180\ g_{sugar})$ of water and B=$134.4\times10^3 mL_{CO_2}\times(2.7\ g_{sugar}/180\ g_{sugar})$ of CO_2. Mathematically converting the release of water and CO_2 into hourly rates gives the water loss due to respiration as WL in $g_w kg^{-1}h^{-1}$ and the respiration rate (RR) in mL_{CO_2} $kg^{-1}h^{-1}$. By combining WL with RR, Equation 4 is derived.

$$WL = 10 \times A/B \times RR \quad (4)$$

where A and B are the coefficients of the previously established stoichiometry.

Texture analysis and microscopic evaluation of tomato skin

Texture analysis was carried out by Texture Analyser TA-XT2i (Stable Micro Systems Ltd., Godalming, UK) as described by Templalexis et al. (2023). The maximum force (FKMF) and the absorbed energy or work (FKW) required to shear tomatoes were estimated from the force-deformation curves (Figure 1), generated by the Texture Exponent software ver. 6.2, as described by Templalexis et al. (2023).

Ultraviolet irradiation has been reported to affect the integrity of tomato skin (Bu et al., 2013; Charles et al., 2008). Given the potential impact of UV-C treatment on the visual perception of tomato skin, as well as on its textural integrity and water transport properties, microscopic examination was conducted to investigate possible structural alterations. A DinoEye Edge 5MP ocular digital camera (Dino-Lite Europe, IDCP B.V., The Netherlands) was mounted on a standard optical microscope (Model XSZ-8D, Kunshan Huanair Precision Instrument Co., Ltd., China) to capture high-resolution images of the tomato epidermis. Observations focused on surface morphology and potential microstructural changes associated with treatment and storage conditions.

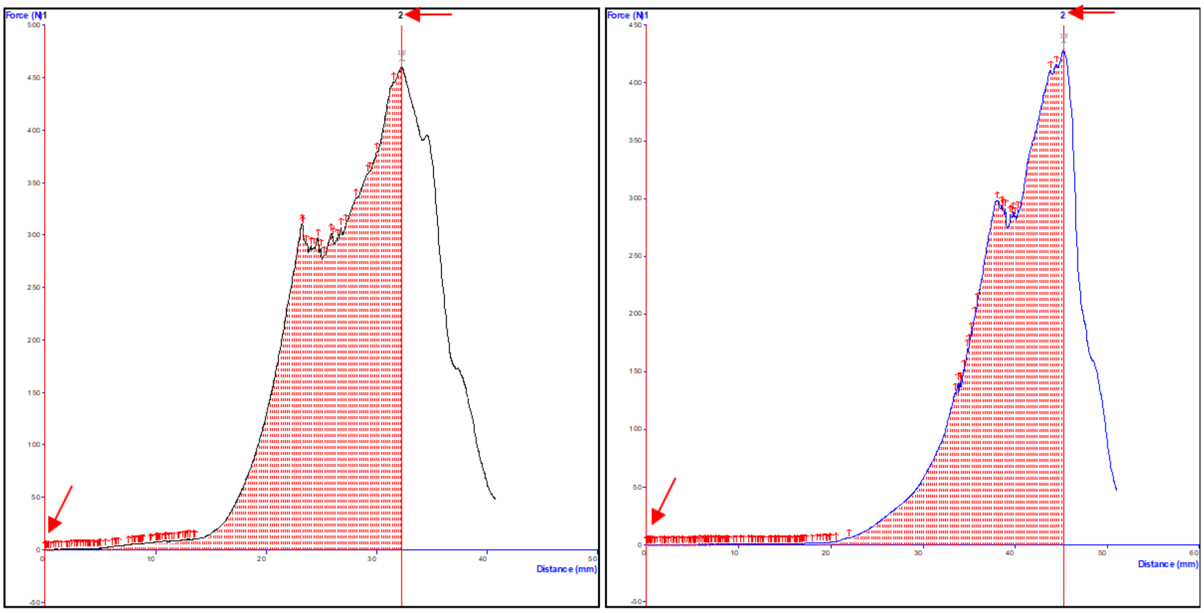

Figure 1: Force–distance curves of whole (left) and fresh-cut (right) tomatoes subjected to UV-C treatment at 0.40 kJ m^{-2} during the Kramer shear cell test. The maximum shear force, work of shear and peak force profile are measured between 1-2 points (red arrows).

Respiration and ethylene rates

The respiration rate (RR) was determined using a closed-static system, as described by Templalexis et al. (2023). Samples were sealed in respiration chambers, and gas accumulation was monitored over time. Carbon dioxide (CO_2) concentration was recorded using a Riken Keiki RI-411A portable CO_2 monitor (Riken Keiki Co., Ltd., Japan), while ethylene (C_2H_4) concentration was measured using a MacView-Gas Analyser (EMS B.V., The Netherlands), which has a resolution of ±0.01 ppm and an accuracy of ±0.5‰. The instruments were connected via a closed-loop plastic tubing system to ensure minimal gas leakage and stable sampling conditions. The respiration rate (mL_{CO_2} $kg^{-1}h^{-1}$) was calculated using the following equation:

$$RR = 10^{-3}(\Delta C/\Delta t)(V/m) \tag{5}$$

where ΔC is the CO_2 accumulation in ppm, V is the headspace volume of the chamber in mL, Δt is the time interval in h, and m is the mass of the tomato sample in g. The ethylene production rate ($\mu L_{C_2h_4}$ $h^{-1}kg^{-1}$) was estimated using:

$$ER = (C/t)(V/m) \tag{6}$$

where C is the ethylene concentration in ppm, V is the headspace volume in L, t is the measurement time in h, and m is the sample mass in kg. The headspace volume was estimated by subtracting the volume of the tomato samples from the total chamber volume. Samples volume was determined at the end of each measurement using the water displacement method.

Colour estimation

Colour measurements were carried out using a portable chroma meter (CR-300, Konica Minolta, Japan), based on the CIE Lab* colour space. For fresh-cut tomatoes, two measurements were taken at distinct spots on the exposed skin surface of each longitudinal section. A total of 3 samples (each containing 14 tomato halves) were analyzed across 3 replicates, yielding 252 colour measurements (2 spots × 3 samples × 3 replicates × 14 halves). For whole tomatoes, colour was assessed at two spots on each side of the fruit, corresponding to both longitudinal sections. Three samples, each consisting of 7 whole tomatoes, were analyzed across 3 replicates, also resulting in 252 measurement points (4 spots × 3 samples × 3 replicates × 7 tomatoes). The following derived colour indices were calculated from a* and b* values:

- Chroma (C*) representing colour intensity, $C^* = (a^{*2}+b^{*2})^{0.5}$,
- Hue angle (h*) indicating the qualitative aspect of colour (eg., red, green), $h^* = \arctan^{-1}(b^*/a^*)$ and
- Colour difference over time (ΔE^*), $\Delta E^* = [(a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2 + (L^*_2 - L^*_1)^2]^{0.5}$ where subscripts 1 and 2 refer to the initial and final colour measurements (Pathare et al., 2013).

Total soluble solids and Total acidity

Filtered tomato juice was used for the determination of total soluble solids (TSS) and total titratable acidity (TA). TSS was measured using a digital refractometer (Model HI96801, HANNA Instruments Ltd, UK) with resolution of ±0.1%. TA was estimated with a digital acidity meter (Model GMK-708, G-won Hitech Co., Ltd., Korea), offering an accuracy of ±0.05% and a resolution 0.01%.

2.3 Statistical analysis

The experiment followed a full factorial design incorporating three independent factors:

i UV-C irradiation at four doses: 0 (control), 0.22, 0.40 and 1.23 kJ m^{-2},

ii Tomato cutting at two forms: whole and fresh-cut,

iii Storage time at five time points: 0, 24, 48, 72 and 96 h.

Analysis of variance (ANOVA) was conducted using Statgraphics Centurion 19 (Statpoint Technologies Inc., Warrenton, VA, USA). Statistical significance was assessed at P-value $\leq$ 0.05. Where statistical significance was analysed between freshly cut and whole tomatoes, or between different treatments, means were compared using the Fisher's least significant difference (LSD) post hoc test and expressed as mean ± LSD. On the contrary, where mean values presented with no statistical significance analysis they were expressed as mean ± standard deviation.

3 Results and Discussion

3.1 Mass loss analysis of fresh-cut and whole tomatoes

The ANOVA results revealed that all main factors, 'UV-C treatment', 'Tomato cutting' and 'Storage time', significantly affected mass loss (P-value $\leq$ 0.001), along with most of their interactions (Table 1). The only non-significant interaction was 'UV-C treatment × Storage time'. Among the main effects, 'Tomato cutting' had the greatest effect, with the highest F-ratio (F-ratio=1669.53) indicating its dominant role in configuration of mass loss. Among the interactions, 'Tomato cutting × Storage time' exhibited the highest F-ratio (F-ratio=146.96) further highlighting the influence of sample form (whole or fresh-cut) on mass loss during cold storage. The significance of the 'Tomato cutting' factor was expected, as mechanical processing increases surface area exposed to environment, thereby enhancing transpiration and mass loss.

The 'UV-C treatment × Tomato cutting' interaction revealed that fresh-cut samples lost significantly more mass, on average 5.44% to 7.66%, than whole tomatoes (0.21% to 1.44%), indicating a more than sevenfold increase. This effect may be attributed to UV-C-induced oxidative stress, which can further compromise cellular integrity, thereby enhancing water loss. In whole tomatoes, however, this additive effect appeared

Table 1: ANOVA of mass loss (%) as affected by ‘Storage time’, ‘UV-C treatment’ and ‘Tomato cutting’.

Source	*df*	*F-ratio*	*P-value*
Main effects			
A: UV-C treatment	3	19.54	≤0.001*
B: Tomato cutting	1	1669.53	≤0.001*
C: Storage time (h)	4	257.33	≤0.001*
Interactions			
A×B	3	22.55	≤0.001*
A×C	12	1.29	0.2240^{NS}
B×C	4	146.96	≤0.001*
A×B×C	12	2.06	0.0192*

*=significant at P≤0.05; df=degree of freedom; All F-ratios are based on the residual mean square error; NS=not significant

minimal, likely due to the dominant influence of the intact cuticle in limiting transpiration. In whole tomatoes, control samples exhibited minimal mass losses (0.4 %) whereas UV-C treatment led to increased losses, with the highest found at 2.65% for 1.23 kJ m^{-2} (Figure 2). This increase is likely due to UV-C-induced structural and physiological changes. UV-C exposure is known to alter the cuticular wax morphology, increasing permeability and, as found in this study, enhancing transpiration. Additionally, high UV-C doses may compromise cell wall integrity, inducing plasmolysis and collapse of epidermal and mesocarp cells, as previously reported (Pinheiro et al., 2015; Ribeiro et al., 2012). Nevertheless, losses remained below 3%, suggesting that marketability was maintained, consistent with Yehoshua and Rodov (2003), who noted that tomatoes remain marketable until mass loss exceeds 7%.

In contrast, fresh-cut tomatoes exhibited substantially higher mass loss (Figure 2). The maximum mass loss was observed at 12.39% for the 0.40 kJ m^{-2} treatment followed by the control (11.06%). The 0.22 and 1.23 kJ m^{-2} treatments resulted in lower losses (9.85% and 9.56%, respectively). The reduction observed at 1.23 kJ m^{-2} may be linked to UV-C-induced tissue hardening, which can reduce water permeability, a response in line with Cote et al. (2013), who reported UV-C-mediated reduction in transpiration in whole tomatoes. Similarly, Charles et al. (2008) observed UV-C-induced flattening of surface cell mounds, indicative of structural modification. These changes were also visually confirmed in this study, through microscopic imaging (Figure 3), which shows clear morphological differences between control and irradiated fruit epidermis.

3.2 Colour analysis of fresh-cut and whole tomatoes

At the end of storage, the L* index (lightness) decreased by 1.6%, in whole and 6.3% in fresh-cut tomatoes. The a* index (redness) decreased by 2.2% in whole and 8.2% in fresh-cut tomatoes. The b* index (yellowness) exhibited the highest change, with a 16.9% reduction in fresh-cut tomatoes compared to 8.5% decrease in whole tomatoes. These results indicate that colour degradation was more pronounced in fresh-cut tomatoes, likely due to enhanced oxidative stress resulting from tissue disruption and exposure to UV-C irradiation. The combined effect of tomato cutting and UV-C irradiation may accelerate pigment degradation, reducing visual quality in a more significant way in fresh-cut fruit. Tissue cutting induces oxidative stress in plants by disrupting cellular compartmentalisation, which activates oxidative enzymes such as polyphenol oxidase (PPO) and peroxidase (POD). This enzy-

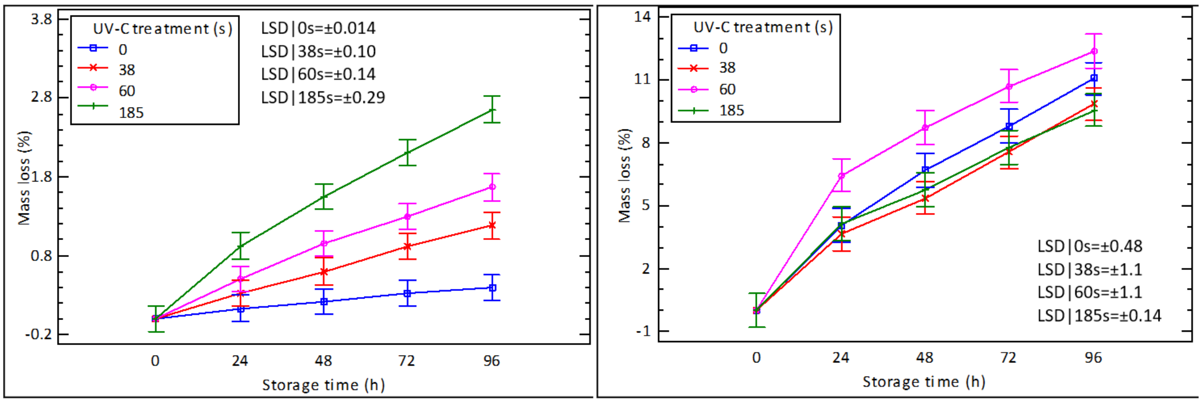

Figure 2: Mass loss (%) of whole (left) and fresh-cut (right) tomatoes during storage as influenced by UV-C treatment. Error bars indicate the least significant difference (LSD) at P $\leq$ 0.05 (Fisher's test). Each data point represents the mean of n = 9 samples.

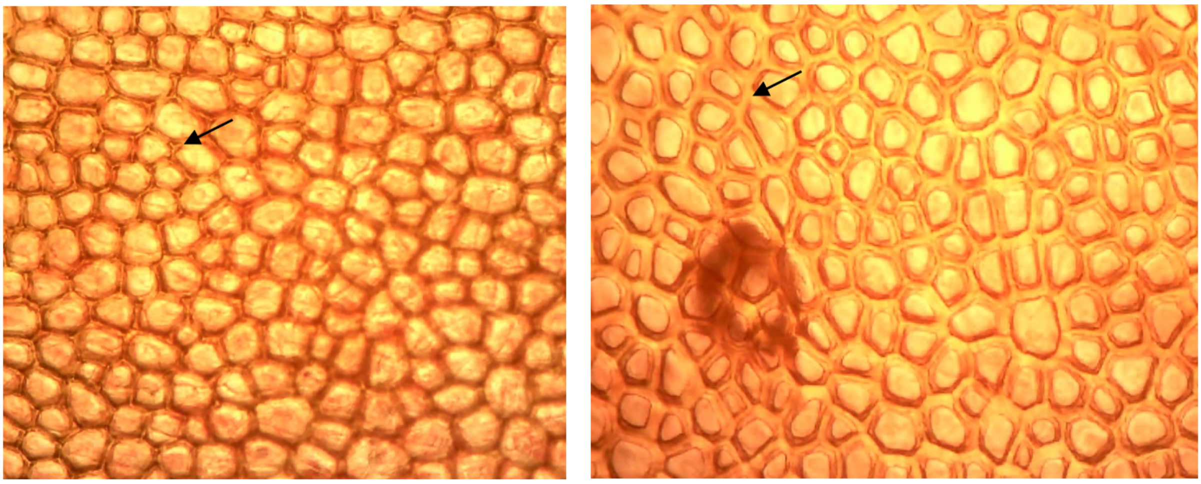

Figure 3: Flattening of epidermal cell mounds in tomato pericarp tissue: control (left) and UV-C irradiated sample at 1.23 kJ m^{-2} (right). The observed structural alteration indicates cell deformation and loss of turgor, likely associated with UV-C-induced stress.

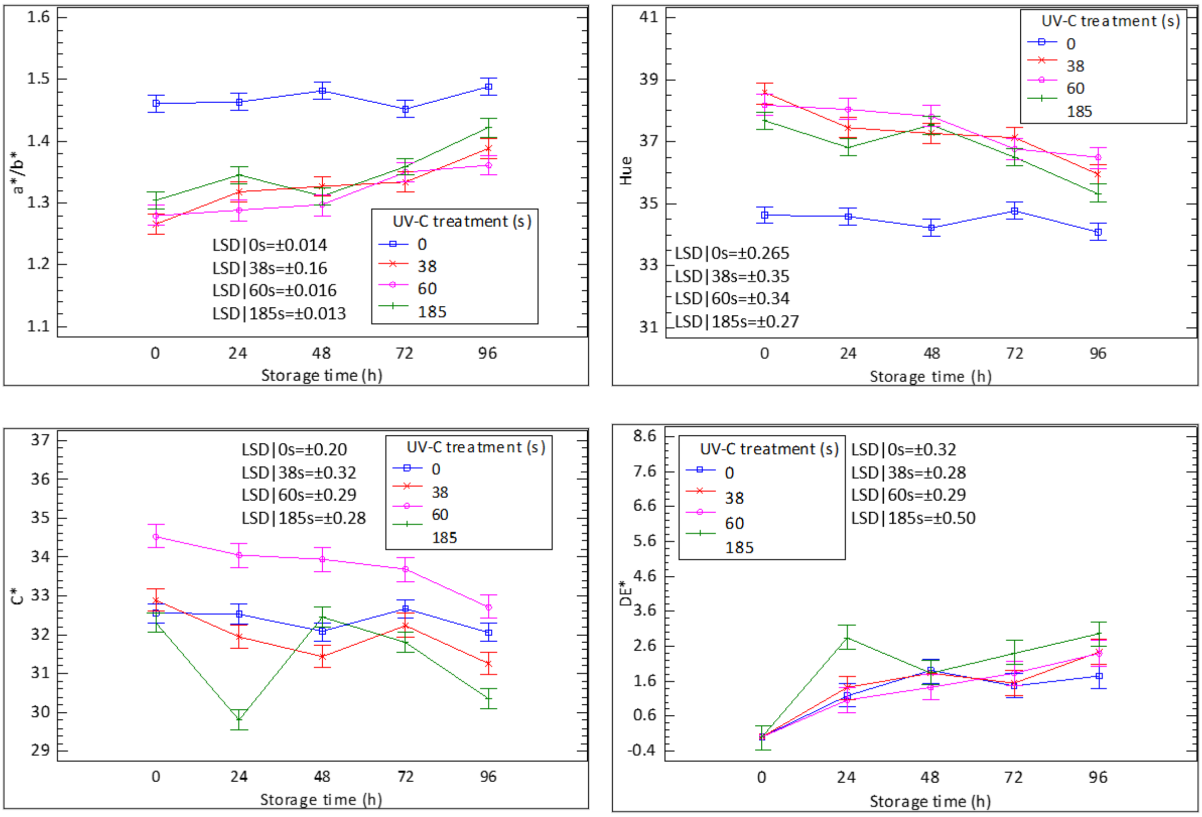

Figure 4: a*/b* ratio, h*, C* and ΔE* of whole tomatoes during storage in relation to UV-C treatment. Error bars indicate the least significant difference (LSD) at $P \leq 0.05$ (Fisher's test). Each point represents the mean of n = 252 sample points.

matic activity can result in browning reactions and modifications of colour parameters, particularly L*, a* and b* values. Additionally, UV-C irradiation may further intensify oxidative stress through generation of reactive oxygen species (ROS). These ROS can alter the activity of antioxidant enzymes and trigger the accumulation of phenolic compounds, both of which can influence tissue colour and stability during storage (Bhat, 2016; Chisari et al., 2011; Zhang et al., 2017).

Following this, colour indices were analysed to assess the 'Tomato cutting × Storage time' interaction. The a*/b* ratio increased over storage time and was significantly different between whole and fresh-cut tomatoes (P-value≤0.001, F-Ratio=10.29) with an increase of 6.6% in whole tomatoes and 10.6% in fresh-cut tomatoes. This increase is attributed to the greater relative reduction of b* compared to a*, leading to an overall shift in chromatic balance.

The hue angle (h*) which reflects the perceived colour tone (with 0^o corresponding to pure red), decreased with storage time, indicating a shift toward a redder hue in both whole and fresh-cut tomatoes. This decrease was significantly different between whole and fresh-cut tomatoes (P-value≤0.001, F-Ratio=10.53), with a 7.2% reduction in fresh-cut and 4.85% in whole tomatoes.

The chroma (C*), representing colour saturation or intensity, also decreased significantly during storage (P-value≤0.001, F-Ratio=77.08), with a more pronounce reduction in fresh-cut tomatoes

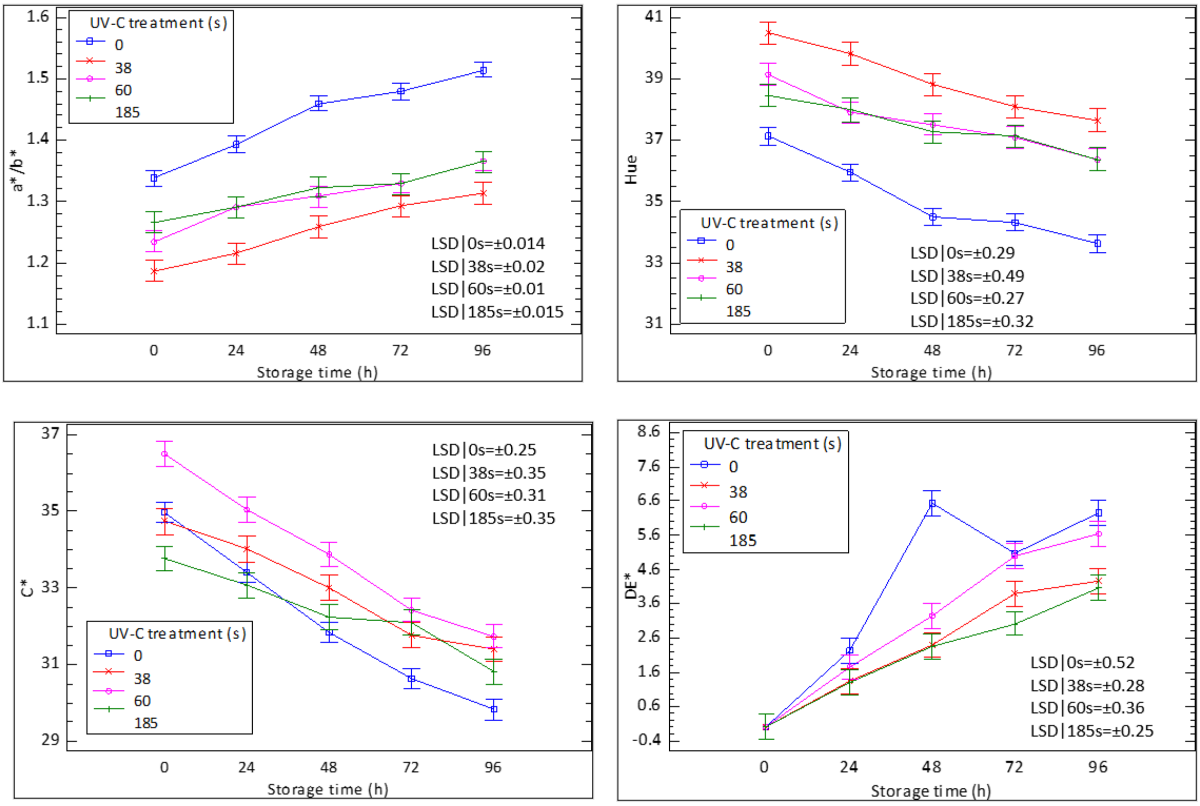

Figure 5: a*/b* ratio, h*, C* and ΔE* of fresh-cut tomatoes during storage in relation to UV-C treatment. Error bars indicate the least significant difference (LSD) at P $\leq$ 0.05 (Fisher's test). Each point represents the mean of n = 252 sample points.

(11.6%) compared to whole tomatoes (4.4%). The reduction in C* reflects a loss in colour brightness and purity, suggesting a more pronounced visual deterioration in fresh-cut tomatoes due to tissue disruption and enhanced oxidative degradation.

Finally, the total colour change (ΔE*), increased over the storage time and was significantly different between whole and fresh-cut tomatoes (P-value$\leq$0.001, F-Ratio=45.15). At the end of storage, fresh-cut tomatoes exhibited a ΔE* of 5.05, more than twice the value in whole tomatoes (ΔE*=2.38). Notable, during the first 24 h, the increase in ΔE* was comparable for whole and fresh-cut tomatoes; however, beyond this point, the rate of colour change accelerated in fresh-cut tomatoes. Joyner and Yadav (2015) reported that a trained eye can differentiate two colours if the value of ΔE*<2. If 2.0< ΔE*<3.5 then there is a slight colour change noticeable by a normal observer but it is still close to the original colour. However, beyond ΔE*>3.5 the colour change becomes quite noticeable. Based on these thresholds, the colour change in whole tomatoes by the end of storage would be slightly perceptible, while in fresh-cut tomatoes, the change would be readily noticeable, indicating a greater visual degradation associated with tissue damage and increased oxidative processes.

Following the analysis of colour indices in whole and fresh-cut tomatoes in relation to the interaction 'Tomato cutting × UV-C treatment', several significant findings emerged. The a*/b* ratio was significantly higher in whole tomatoes compared to fresh-cut tomatoes (P-value$\leq$0.001, F-Ratio=12.43) apart from the 0.40 kJ m^{-2}

treatment, where no statistical significant difference was observed between fresh-cut, 1.30±0.007 and whole tomatoes, 1.31±0.007. The h* index exhibited significantly higher values in fresh-cut tomatoes than in the whole tomatoes (P-value≤0.001, F-Ratio=17.52), again with the 0.40 kJ m^{-2} treatment showing no statistical difference between fresh-cut, 37.59±0.14 and whole tomatoes, 37.47±0.14.

Regarding chroma (C*), fresh-cut tomatoes showed significantly higher values under UV-C treatment (P-value≤0.001, F-Ratio=26.33), whereas control tomatoes exhibited higher C* values in whole tomatoes. For the 0.40 kJ m^{-2} treatment, there was no significant difference between fresh-cut, 33.91±0.15 and whole tomatoes, 33.78±0.15.

Finally, total colour difference (ΔE*) was significantly higher in fresh-cut tomatoes for both the control and UV-C treated tomatoes (P-value≤0.001, F-Ratio=42.14), except in the case of the 1.23 kJ m^{-2} treatment, where no statistical difference was observed between fresh-cut, 2.15±0.3 and whole tomatoes, 2.0±0.3. The highest ΔE* variation was observed in fresh-cut control tomatoes (ΔE*=4.0), while in whole tomatoes, the highest ΔE* occurred under the 1.23 kJ m^{-2} treatment (ΔE*=2.0).

In whole tomatoes, UV-C irradiation only slightly affected the colour change, with mean ΔE* values ranging between 1.26 and 2.0, indicating minimal perceptible differences. In contrast, the colour change in fresh-cut tomatoes was more visible with the highest mean ΔE*=4.02 observed in control tomatoes, followed by the 0.40 kJ m^{-2} UV-C treatment (ΔE*=3.13). The other two treatments had lower ΔE* values (<2.38), indicating visible colour change.

The tested storage period, although relatively short, resulted in no significant colour change in whole tomatoes. On the contrary, a reduction in red colour intensity was observed in fresh-cut tomatoes, with the most pronounced decreases noted in the control tomatoes (10.64%) and the 0.40 kJ m^{-2} treatment (9.60%). The 0.22 kJ m^{-2} and 1.23 kJ m^{-2} treatments showed smaller reductions (5.9% and 6.2%, respectively). These differences can be attributed to the combined effects of tissue disruption due to cutting and UV-C-induced oxidative stress, which influence tomato physiology.

Cutting has been widely reported to induce oxidative stress by disrupting cellular compartments, leading to the activation of oxidative enzymes (PPO, POD). This enzymatic activity can promote browning and changes in colour indices. UV-C irradiation deteriorates oxidative stress by generating reactive oxygen species (ROS), which in turn may modify antioxidant enzyme activity and enhance accumulation of phenolic compounds (Bhat, 2016; Chisari et al., 2011; Zhang et al., 2017).

Figures 4 and 5 show the quantitative and qualitative colour characteristics of fresh-cut and whole tomatoes, expressed by the indices a*/b*, h*, C* and ΔE*. The a*/b* ratio is indicative of redness development, which is critical in evaluating tomato ripening and visual quality. Both whole and fresh-cut tomatoes showed significantly higher a*/b* values in control tomatoes, with a mean value of 1.47±0.2 for whole and 1.44±0.2 for fresh-cut tomatoes. In contrast, UV-C treated tomatoes showed significant lower a*/b* values. Specifically, for whole tomatoes, a*/b* ranged between 1.32±0.2 and 1.35±0.2, while in fresh-cut tomatoes, between 1.25±0.2 and 1.31±0.1. These results indicate that UV-C irradiation led to reduction of the a*/b* ratio, suggesting a slight inhibition of red pigment development or a relative increase in yellow hue components, which may be attributed to oxidative degradation and enzymatic browning induced by tissue disruption as previously discussed.

Statistical analysis revealed no significant differences between the 0.22 kJ m^{-2} and 0.40 kJ m^{-2} treatments in whole tomatoes and between the 0.40 kJ m^{-2} and 1.23 kJ m^{-2} treatments in fresh-cut tomatoes. However, the remaining UV-C treatment and control, exhibited statistically significant differences in both whole and fresh-cut tomatoes (see Figures 4 and 5), underscoring the differential response of colour development to UV-C dose and cutting. The a*/b* for the control tomatoes exhibited a slight increase of 1.9% in whole tomatoes at the end of cold storage, whereas in fresh-cut tomatoes the increase was significantly higher at 13.2% (see Figures 4 and 5). This pronounced difference is likely attributed to the cutting-induced stress, which accelerates the metabolic and oxidative processes, thereby promoting faster changes in colour indices. Among the UV-C treatments whole tomatoes treated with 0.40 kJ m^{-2}, showed a 6.3% increase in, a*/b*, while those treated with 0.22 and 1.23 kJ m^{-2} exhibited increases of approximately 9%. In fresh-cut samples, the 1.23 kJ m^{-2} treatment, resulted in a 7.9% increase, while the 0.22 and 0.40 kJ m^{-2} treatments in a 10% increase. Notably, throughout storage, fresh-cut tomatoes treated with 0.22 kJ m^{-2} dose consistently exhibited the lowest a*/b* values, a response possibly linked to the combined effect of UV-C dose and tissue physiology, including enzyme inactivation involved in pigment metabolism.

Analysis of the hue angle (h*) further confirmed significant differences between the control and the UV-C treated samples, for both fresh-cut and whole tomatoes (Figures 4 and 5). In those figures, control tomatoes maintained redder hues compared to the UV-C irradiated samples, consistent with the a*/b* trends. Hue changes were also more pronounced in fresh-cut tomatoes, reinforcing the role of tissue damage and oxidative stress in colour variation. Specifically, the h* reduction in fresh-cut tomatoes, ranged from 5.4% in the 1.23 kJ m^{-2} treatment, to 9.4% in the control. In whole tomatoes, the greatest reduction (6.8%) was observed in the 0.22 kJ m^{-2} treatment whereas the control exhibited the lowest reduction (1.6%).

Among treatments, the 0.40 kJ m^{-2} UV-C dose consistently exhibited the highest C* values throughout storage in fresh-cut and whole tomatoes, indicating better colour saturation and retention. In fresh-cut tomatoes, the reduction in C* ranged from 8.8% to 14.7%, with the greatest reduction observed in the control tomatoes, likely due to the combined effects of cutting-induced oxidative stress and increased tissue exposure to air, which accelerate pigment degradation and colour dulling. In contrast, UV-C treatments appeared to mitigate these effects, as indicated by the lower reduction rates (8.8-13.0%) relative to the control tomatoes. For whole tomatoes, the reduction in C* was significantly lower, ranging from 1.5% to 6.1%, with the highest loss recorded at the 1.23 kJ m^{-2} dose. These findings suggest that whole fruit structure offers better protection against colour degradation, and that higher UV-C doses may adversely affect pigment stability, possibly due to increased oxidative stress or modifications in cuticle permeability. Overall, UV-C treatment at 0.40 kJ m^{-2} appears most effective in maintaining colour intensity in both fresh-cut and whole tomatoes during short-term storage.

Fresh-cut tomatoes exhibited a more pronounced total colour change (ΔE*) during storage compared to whole tomatoes (Figures 4 and 5). At the end of the storage period, ΔE* in fresh-cut samples ranged from 4.06 to 6.23, whereas in whole tomatoes from 1.73 to 2.95. The lowest ΔE* value in fresh-cut tomatoes was observed for the 1.23 kJ m^{-2} UV-C treatment (ΔE*=4.06), while the highest was observed in the control (ΔE*=6.23). Conversely, in whole tomatoes, the lowest ΔE* was found in the control (ΔE*=1.73), and the highest in the 1.23 kJ m^{-2} treatment (ΔE*=2.95). These results indicate that UV-C irradiation delayed the progression of colour change in fresh-cut tomatoes, an effect not clearly observed in whole fruits.

Previous studies confirm that UV-C irradiation can retard colour development in tomatoes by interfering with ripening processes. In the present study, despite the short storage duration, which simulated commercial fresh-cut conditions as has been explained this retardation effect was evident in fresh-cut tomatoes. Bu et al. (2013) showed that exposure of mature-green cherry tomatoes (cv. *Zhenzhu*) to 4.2 kJ m^{-2} dose delayed colour development over 35 days at 18 ^{o}C. Similarly, Obande et al. (2011) reported a delayed loss of green colour in ripe-green tomatoes (cv. *Mecano*), although no significant differences were observed in red-ripe fruits treated with 3.0 and 8.0 kJ m^{-2} doses. Lu et al. (2016) reported that colour retention post UV-C treatment was ripening stage-dependent, with the 'breaker stage' showing the most pronounced response (Charles et al., 2016). In contrast, Kim et al. (2008) found no significant effect of UV-C dose (19.2 kJ m^{-2}) on colour indices (L*, a*, b*, C*, h*) or lycopene content in fresh-cut ripe tomato slices after one week at 4-6 ^{o}C. Similarly, Artés-Hernández et al. (2021) reported that UV-C doses up to 7.2 kJ m^{-2} did not affect the lycopene content of fresh-cut watermelon after one week of storage. These contrasting findings highlight the influence of commodity type, physiological maturity, and UV-C dose on the effectiveness of UV-C treatments in shaping post-harvest colour dynamics.

3.3 Texture analysis

Table 2 presents the ANOVA results for two texture properties, F|max and work, analysed in whole tomatoes under factors 'Storage time' and 'UV-C treatment'. For whole tomatoes, F|max was significantly affected by both the 'UV-C treatment' and the interaction 'UV-C treatment $\times$ Storage time'. The work of shear was significantly affected by both 'Storage time' and 'UV-C treatment'. In fresh-cut tomatoes, F|max was significantly affected by both 'UV-C treatment' and 'Storage time'. The work of shear was significantly affected by 'Storage time', 'UV-C treatment' and their interaction.

Figure 6 presents the changes in F|max and work of shear at the beginning and at the end of cold storage for whole and fresh-cut tomatoes subjected to different UV-C treatments. In whole tomatoes, the F|max values remained largely unchanged across treatments between the 0^{th} and 4^{th} day, except for the 0.40 kJ m^{-2} treatment, which showed a significant 18.7% decrease. The control differed significantly from the 0.22 kJ m^{-2} and 0.40 kJ m^{-2} treatments at the end of the cold storage, while a significant difference was observed between 0.22 kJ m^{-2}, 0.40 kJ m^{-2} and 1.23 kJ m^{-2} treatments. In terms of work of shear, at the end of the cold storage, significantly higher values were observed the 0.22 kJ m^{-2} dose compared to 0.4 kJ m^{-2} and 1.23 kJ m^{-2} treatments (Figure 6). Between the 0^{th} and 4^{th} day, a 16.4% decrease in work of shear was noted in control samples, and a significant decrease of 22.5% in the 0.40 kJ m^{-2} treatment. No significant reductions were observed for the other UV-C treatments. For fresh-cut tomatoes, F|max decreased significantly after 4 days (96 days) of storage across all treatments except for the 1.23 kJ m^{-2} dose. The control tomatoes showed the greatest reduction (28.5%), followed by 0.40 kJ m^{-2} (19.9%), while the 1.23 and 0.22 kJ m^{-2} treatments both exhibited similar, lower reductions (14.7% and 14.6%, respectively). These findings suggest that at the end of storage, UV-C treated fresh-cut tomatoes required higher F|max values than the control tomatoes, indicating better structural integrity. Regarding work of shear, UV-C treated fresh-cut tomatoes required significantly more energy at the beginning of storage (0^{th} day), as indicated by the significantly higher initial values. The reduction in work of shear at the end of the storage (4^{th} day) was significantly higher than the decrease in F|max,, with greatest reduction seen in 0.22 kJ m^{-2} (37.8%) followed by 0.40 kJ m^{-2} (34.4%), while the control tomatoes and 1.23 kJ m^{-2} treatment showed reductions of 21.7% and 21.5% respectively (Figure 6). In the Kramer shear-cell tests, the F|max and the work of shear are important indicators of tissue firmness and resistance to mechanical stress. The observed variations between whole and fresh-cut tomatoes can be attributed to UV-C induced modulation of fruit softening enzymes and tissue integrity. Bu et al. (2013) reported that UV-treatment preserved firmness in tomatoes during 35 days of storage at 18 ^{o}C by inhibiting cell-wall degrading enzymes such as cellulase, polygalacturonase (PG), and pectin methylesterase (PME). Lu et al. (2016) similarly attributed firmness retention to delayed protopectin solubilization and reduced PG and PME activity in UV-treated tomatoes. Enhanced firmness following UV-C exposure, has also been observed in various cultivars such as Mecano (Obande et al., 2011), Flavortop (Tiecher et al., 2013), and Elpida (Cote et al., 2013). However, cultivar-dependent responses to UV-C have been noted. In contrast, Liu et al. (2009) and Castagna et al. (2013) reported a negative effect on firmness in cultivars *Red Ruby* and *Moneymaker*, indicating that the impact of UV-C on fruit texture is genotype-specific and may be influenced by ripening stage, dose, and post-treatments.

3.4 Respiration rate

The effect of UV-C irradiation on respiration rate is critical, as it is a key metabolic indicator affecting the postharvest quality and shelf-life. The ANOVA results in Table 3 show statistically sig-

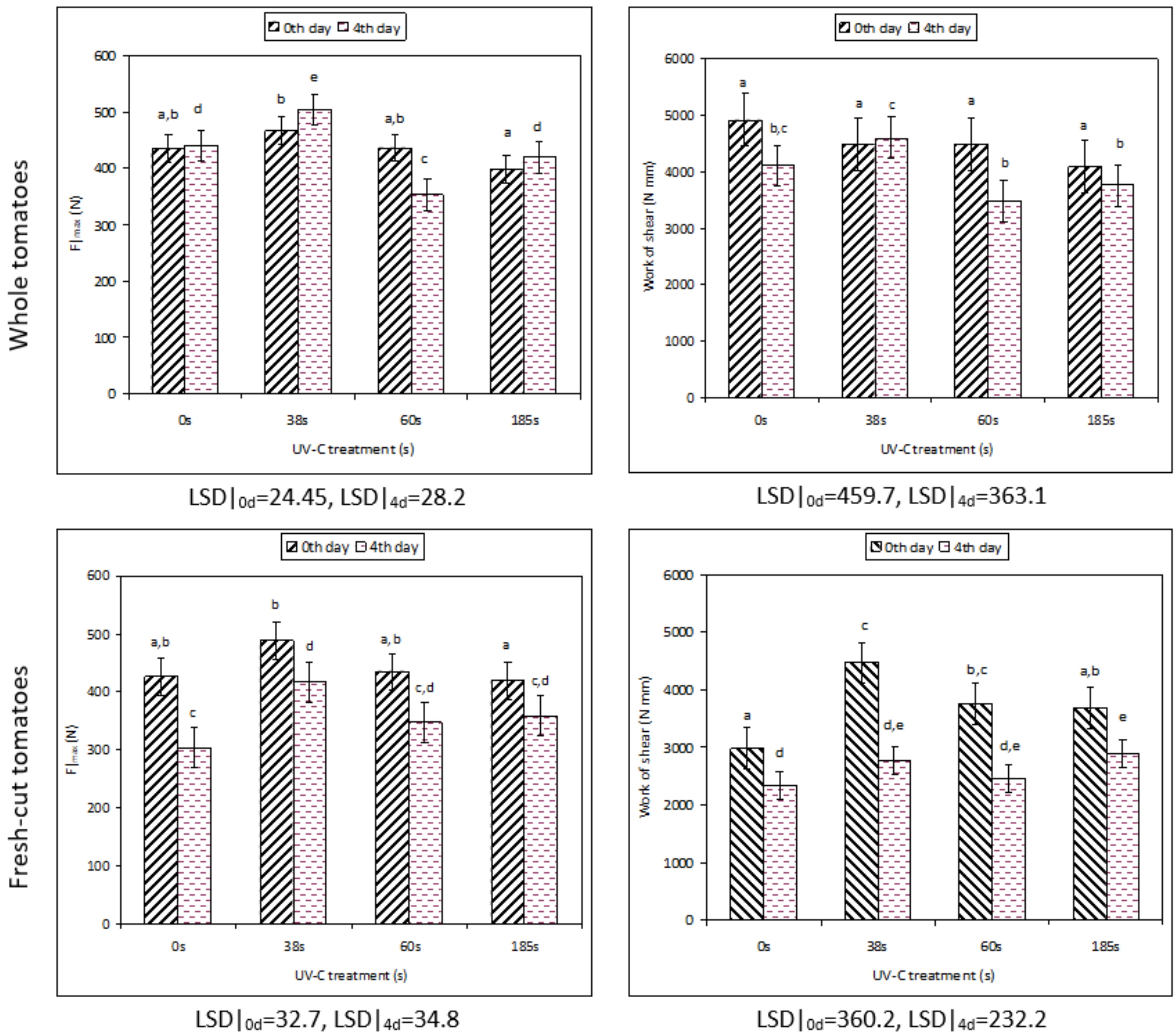

Figure 6: F|max and work of shear at the beginning (0^{th} day) and end (4^{th} day) of storage for whole and fresh-cut tomatoes under UV-C treatment. Error bars indicate the least significant differences (LSD) at P $\leq$ 0.05 (Fisher's test). Each point represents the mean of n = 3 samples. Values with different superscripts within the same day (0^{th} or 4^{th}) are significantly different (P $\leq$ 0.05, Fisher's test).

Table 2: ANOVA of F|max (N) and work of shear (N mm) in whole and fresh-cut tomatoes as affected by ‘Storage time’ and ‘UV-C treatment’.

	Factor	*df*	F|max (N)		Work (N mm)	
			F-Ratio	P-Value	F-Ratio	P-Value
Whole tomatoes	A: Storage time (d)	1	0.14	0.7125^{NS}	7.97	0.0122*
	B: UV-C treatment	3	11.98	0.0002*	3.38	0.0445*
	Interactions: A×B	3	5.40	0.0093*	1.99	0.1568^{NS}
Fresh-cut tomatoes	A: Storage time (d)	1	33.75	≤0.001*	70.80	≤0.001*
	B: UV-C treatment	3	6.54	0.0043*	9.32	0.0008*
	Interactions: A×B	3	0.80	0.5099^{NS}	3.31	0.0472*

* = significant at P≤0.05; df=degree of freedom; All F-ratios are based on the residual mean square error, NS=not significant.

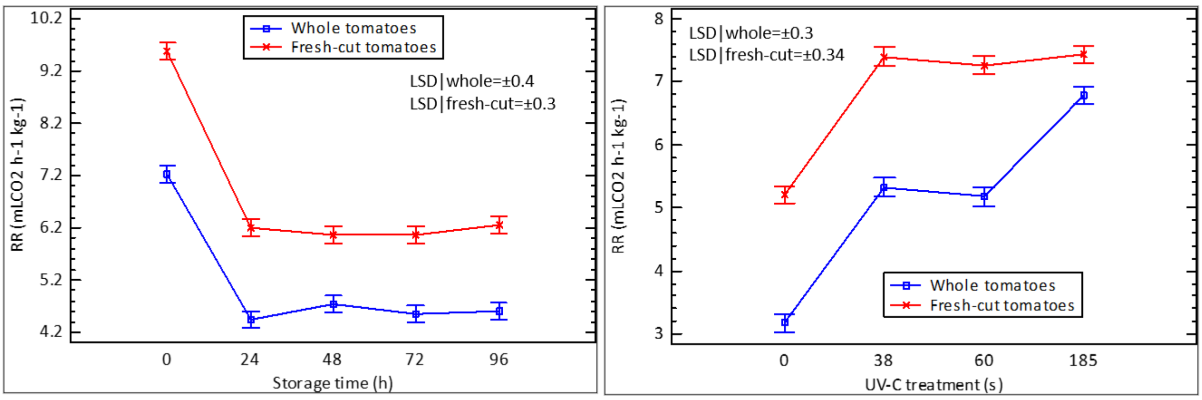

Figure 7: RR (mL$_{CO_2}$ h^{-1} kg^{-1}) of whole and fresh-cut tomatoes as a function of storage time (left) and UV-C treatment (right). Error bars represent the least significant difference (LSD) at P $\leq$ 0.05 (Fisher’s test). Each point represents the mean of n = 9 samples.

Table 3: ANOVA of RR (mL_{CO_2} h^{-1} kg^{-1}) as affected by 'Tomato cutting', 'Storage time', and 'UV-C treatment'.

Factor	df	F-Ratio	P-Value
A: Tomato cutting	1	603.11	≤0.001*
B: UV-C treatment	3	321.73	≤0.001*
C: Storage time	4	303.43	≤0.001*
Interactions			
A×B	3	25.90	≤0.001*
A×C	4	6.37	0.001*
B×C	12	35.49	≤0.001*
A×B×C	12	2.41	0.0053*

* = significant at P≤0.05; df=degree of freedom; All F-ratios are based on the residual mean square error.

nificant effects (P-value≤ 0.001) of the main factors, 'Tomato cutting', 'Storage time' and 'UV-C treatment' as well their interactions. Among these, the interactions 'Tomato cutting × UV-C treatment' and 'UV-C treatment × Storage time' had the highest F-Ratios, 25.90 and 35.49 respectively. The most dominant factor affecting RR was 'Tomato cutting' (F-Ratio=603.11), surpassing those of 'Storage time' (F-Ratio=303.43) and 'UV-C treatment' (F-Ratio=321.73).

Figure 7 show that whole tomatoes consistently exhibited significantly lower RR than fresh-cut tomatoes across storage time and UV-C treatment. Considering storage time, RR in both whole and fresh-cut tomatoes decreased during the first 24 h and subsequently remained constant. Considering UV-C treatment, an increased trend in RR was observed compared to the control tomatoes (Figure 7). In whole tomatoes, RR significantly increased with UV-C dose, with no significant difference found between the 0.22 kJ m^{-2}, 5.33±0.3mL_{CO_2} h^{-1} kg^{-1} and 0.40 kJ m^{-2}, 5.17±0.3mL_{CO_2} h^{-1} kg^{-1} treatments, while the 1.23 kJ m^{-2} treatment, yielded the highest RR=6.78±0.3mL_{CO_2} h^{-1} kg^{-1}.

In contrast, fresh-cut tomatoes did not exhibit significant RR differences among the UV-C treatments (7.27-7.43±0.34mL_{CO_2} h^{-1} kg^{-1}) though all were significantly higher than the control (5.21±0.34mL_{CO_2} h^{-1} kg^{-1}). This indicates that RR in fresh-cut samples was influenced not only by UV-C exposure but also by the wounding stress induced by cutting. For example, RR in UV-C treated fresh-cut tomatoes increased by 60% for 0.22 kJ m^{-2} and 0.40 kJ m^{-2} and by 92% for 1.23 kJ m^{-2}, relative to the control tomatoes (Figure 7). Furthermore, comparing the control samples of whole and fresh-cut tomatoes revealed a significant 64% increase in RR in the fresh-cut tomatoes (5.21 vs. 3.17 ± 0.13mL CO_2 h^{-1} kg^{-1}), emphasizing the significant impact of mechanical injury on metabolic activity.

The ANOVA for RR considering only 'Storage time' and 'UV-C treatments' factors, confirmed the significance of both factors and their interactions (P-value≤0.001). For whole tomatoes, the dominant factor was 'UV-C treatment' (F-ratio = 175.44), while for fresh-cut tomatoes the 'Storage time' had the highest effect (F-ratio = 275.76). In whole tomatoes, the 1.23 kJ m^{-2} treatment maintained the highest RR throughout storage, while the 0.22 and 0.40 kJ m^{-2} treatments followed similar RR trends, each significantly higher than the control tomatoes. At the beginning of storage, for the respective 0.22 kJ m^{-2}, and 0.40 kJ m^{-2} treatments, RR=7.36±0.5mL_{CO_2} h^{-1} kg^{-1} and RR=7.37±0.5mL_{CO_2} h^{-1} kg^{-1} were 2.37-fold (135%) greater than the control tomatoes, RR=3.10±0.5mL_{CO_2} h^{-1} kg^{-1}, and for the 1.23 kJ m^{-2} treatment, RR=11.0±0.5mL_{CO_2} h^{-1} kg^{-1} increased by 3.6-fold (256%). These results suggest that UV-C exposure induces metabolic stress responses, thereby elevating respiration rate. In fresh-cut tomatoes, the highest RR was also observed at the beginning of the storage in the 1.23 kJ m^{-2} treatment, 11.95±0.4mL_{CO_2} h^{-1} kg^{-1}. Although differences among UV-C doses were not statistically significant, all were significantly higher than the control tomatoes. This response reinforces the conclusion that UV-C exposure triggers oxidative stress responses in both whole and fresh-cut tomatoes.

The literature supports these findings. Vunnam et al. (2014) reported increased respiration in cherry tomatoes irradiated with 3.7 kJ m^{-2} UV-C, while Cote et al. (2013) observed no effect at 4.0 kJ m^{-2}, and Bu et al. (2013) documented RR reduction due to inhibited cell-wall degradation. Moreover, cutting alone, independent of UV-C or sanitizing interventions, leads to tissue trauma, which initiates stress-related metabolic pathways, elevating respiration and accelerating senescence (Lu et al., 2016). This cutting-induced stress likely synergizes with UV-C-mediated oxidative responses, increasing RR and contributing to faster ripening and quality loss.

3.5 Total soluble solids and Total acidity

Table 4 presents the ANOVA results for total soluble solids (TSS) and total acidity (TA) in whole and fresh-cut tomatoes as affected by 'Storage time', 'UV-C treatment' factors, and their interaction. The analysis revealed that, for whole tomatoes, only the 'UV-C treatment' had a significant effect on TSS. In contrast, for fresh-cut tomatoes, both 'Storage time' and 'UV-C treatment' significantly affected TSS content.

In whole tomatoes, all UV-C treated samples exhibited significantly lower TSS values compared to the control at both the beginning (0^{th} day) and end (4^{th} day) of cold storage, 0 kJ m^{-2}: 8.8±0.4%, 0.22 kJ m^{-2}: 7.2±0.4%, 0.40 kJ m^{-2}: 7.0±0.4% and 1.23 kJ m^{-2}: 6.6±0.4%. However, there were no significant differences among the UV-C treatments themselves. The most pronounced TSS reduction was observed in the 1.23 kJ m^{-2} treatment, which resulted in values of 6.5±0.4% (day 0^{th}) and 6.7±0.6% (day 4^{th}), representing a 25.2% decrease compared to the control (8.2±0.4% on day 0^{th}; 9.4±0.6% on day 4^{th}). A similar trend was observed in fresh-cut tomatoes, where the 1.23 kJ m^{-2} treatment also had the lowest TSS (6.3±0.2%, 0^{th} day and 7.0±0.3%, 4^{th} day), corresponding to a 22.1% reduction relative to the control tomatoes (8.3±0.2%, 0^{th} day and 8.7±0.3%, 4^{th} day). At the end of the cold storage, TSS increased in all samples. In whole tomatoes, the control showed the highest TSS increase (+14.6%, from 8.2±0.7% on day 0^{th} to 9.4±0.7% on day 4^{th}), while the 0.22 kJ m^{-2} treatment showed the smallest increase (+1.9% from 7.1±0.7% to 7.2±0.7%). The 0.40 kJ m^{-2} and 1.23 kJ m^{-2} treatments showed intermediate increases of 4.9% and 2.6%, respectively. In fresh-cut tomatoes an increase in TSS was also observed by the end of storage (day 4^{th}), primarily due to the mass loss, and secondarily due to carbohydrate metabolism, starch degradation and soluble sugar accumulation, especially since the tomatoes were harvested at the red ripe stage. The control tomatoes showed an increase of 4.4%, while the 0.40 kJ m^{-2} treatment increased by 5%. The most pronounced increases occurred in the 0.22 and 1.23 kJ m^{-2} treatments (+10.5%, from 6.3±0.34%, day 0^{th} to 7.0±0.34%, day 4^{th}).

Regarding TA, only the 'Storage time × UV-C treatment' interaction significantly affected the ascorbic acid content in fresh-cut tomatoes (Table 4). In whole tomatoes, citric acid content increased with UV-C dose at day 0^{th}, but by day 4^{th}, different trends were noted. The control and 0.22 kJ m^{-2} treatments showed increased TA values from 0.44±0.5% to 0.78±0.5% and 0.41±0.5% to 0.87±0.5%, respectively, whereas the 0.40 kJ m^{-2} and 1.23 kJ m^{-2} treatments showed decreases, from 0.66±0.5% to 0.59±0.5% and 0.97±0.5% to 0.61±0.5%, respectively. Notably, in fresh-cut tomatoes, the 1.23 kJ m^{-2} dose caused a 71.8% decrease in TA, from 1.46±0.5% to 0.41±0.5%.

These results are in partial agreement with the literature. Pinheiro et al. (2015) reported significantly lower TA (in terms of citric acid) in UV-C treated tomatoes compared to controls on day 7. Charles et al. (2005) found minimal changes in TA in UV-treated tomatoes, with significant in-

Table 4: ANOVA of TSS and TA in whole and fresh-cut tomatoes as affected by 'Storage time' and 'UV-C treatment'.

	Factors	*df*	Total Soluble Solids		Acidity (Citrus)		Acidity (Orange)	
			F-Ratio	P-Value	F-Ratio	P-Value	F-Ratio	P-Value
Whole tomatoes	A: Storage time (d)	1	3.88	0.066^{NS}	0.29	0.5986^{NS}	0.18	0.6803^{NS}
	B: UV-C treatment	3	17.33	≤0.001*	0.23	0.8716^{NS}	0.44	0.7289^{NS}
	Interaction A×B	3	1.16	0.3543^{NS}	1.18	0.3502^{NS}	1.33	0.3007^{NS}
Fresh-cut tomatoes	A: Storage time (d)	1	20.45	0.0003*	2.44	0.1376^{NS}	3.28	0.0889^{NS}
	B: UV-C treatment	3	65.69	≤0.001*	1.06	0.3921^{NS}	1.64	0.2205^{NS}
	Interaction A×B	3	0.66	0.5857^{NS}	2.73	0.0780^{NS}	3.40	0.0434*

* = significant at P≤0.05; df=degree of freedom; All F-ratios are based on the residual mean square error, NS=not significant.

creases only in the control after one week of storage. Similarly, Cote et al. (2013) observed decreased TA in UV-C treated tomatoes. Shahbaz et al. (2018) also noted a significant reduction in ascorbic acid in UV-C treated tomatoes. However, in contrast to the current findings, most studies report no effect of UV-C irradiation on TSS (Charles et al., 2005; Cote et al., 2013; Kasim & Kasim, 2015; Liu et al., 2009; Vunnam et al., 2014). These discrepancies may be due to cultivar differences, maturity stage at harvest, or experimental conditions such as UV-C dose, irradiation geometry and storage conditions.

3.6 Ethylene production

Table 5 presents The ANOVA results for ethylene production in relation to the factors 'UV-C treatment', 'Tomato cutting', 'Storage time' and their interactions. This analysis showed that ethylene production was significantly affected by the 'Tomato cutting', 'Storage time', and 'Tomato cutting × Storage time' interaction.

Comparative analysis showed that fresh-cut tomatoes produced significantly higher ethylene than whole tomatoes for all storage points (24, 72 and 96 h). At 72 h, ethylene production was 0.163±0.12 μL kg^{-1} h^{-1} in whole tomatoes and 0.607 ± 0.12 μL kg^{-1} h^{-1} in fresh-cut tomatoes, representing a 3.7-fold increase. At 96 h, ethylene production further diverged, reaching 0.156±0.33 μL kg^{-1} h^{-1} in whole tomatoes and 1.197±0.33 μL kg^{-1} h^{-1} in fresh-cut samples, a 7.7-fold increase. At 24 h, a statistically significant difference was observed between the two tomato groups (whole: 0.094±0.05 μL kg^{-1} h^{-1}, fresh-cut: 0.237±0.05 μL kg^{-1} h^{-1}), indicating that the influence of wounding on ethylene production becomes more pronounced during the later stages of storage.

These findings are consistent with the known wound-induced ethylene biosynthesis in climacteric fruits such as tomatoes. Severo et al. (2015) reported that while UV-C irradiation at 3.7 kJ m^{-2} dose delayed ripening, it also stimulated ethylene production, especially in the initial hours after irradiation in *MicroTom* tomatoes stored for 12 days at 20 ^{o}C. Similarly, Lu et al. (2016) found that UV-C exposure in sliced/wounded tomatoes delayed the peak of ethylene production, suggesting a potential configuration of ripening through suppression of the

Table 5: ANOVA of ethylene production as affected by 'UV-C treatment', 'Tomato cutting' and 'Storage time'.

Factor	*df*	F-Ratio	P-Value
A: UV-C treatment	3	1.23	0.3088^{NS}
B: Tomato cutting	1	26.30	$\leq$0.001*
C: Storage time (h)	4	7.83	0.0011*
Interactions			
A×B	3	1.17	0.3317^{NS}
A×C	12	1.91	0.0990^{NS}
B×C	4	6.22	0.0040*
A×B×C	12	1.76	0.1284^{NS}

* = significant at P≤0.05; df=degree of freedom; All F-ratios are based on the residual mean square error, NS=not significant.

wound response. These studies highlight the dual role of UV-C radiation in formulating ethylene biosynthesis: transient stimulation shortly after application, followed by delayed ripening responses, depending on the dosage, cultivar, and tissue integrity.

3.7 Quantifying water loss due to transpiration and respiration

Water losses in tomatoes were evaluated based on the transpiration rate per unit mass (TR_m) whilst taking into account losses due to water vapour pressure deficit (WVPD) and respiratory metabolism. To distinguish between these two mechanisms, water loss due to respiration was first calculated according to Equation 4. The net transpiration rate per unit mass ($TR_{m|net}$=TR_m-WL, expressed in g_w kg^{-1} h^{-1}) was then obtained by subtracting the respiratory water loss (WL) from the total TR_m, thus isolating the component associated with WVPD. Table 6 presents the transpiration rates for all UV-C treatments applied to both whole and fresh-cut tomatoes. Analysis revealed that respiratory water loss contributed significantly less to total water loss than transpiration across all treatments. In whole tomatoes, respiratory losses accounted for 1.7% to 5.7% of the transpiration losses, with the lowest contribution in the 1.23 kJ m^{-2} treatment, and the highest in control tomatoes. In fresh-cut tomatoes, this contribution was even smaller, ranging from 0.3% to 0.5%, with control tomatoes showing the lowest and the 1.23 kJ m^{-2} dose the highest values. Although the transpiration rate was generally higher in fresh-cut tomatoes, only whole tomatoes exhibited a significant increase in TR_m with increasing UV-C dose (Table 6). This can be attributed to UV-C-induced increases in surface temperature, which in turn enhanced evaporative water loss. The difference in barrier properties between intact skin (in whole fruits) and exposed tissues (in fresh-cut tomatoes) significantly affects the mechanisms and magnitude of transpiration. Whole tomatoes possess greater resistance to water transport, whereas fresh-cut tomatoes, with disrupted epidermis, allow for faster moisture diffusion and evaporation.

According to the ANOVA results in Table 7, TR_m was significantly influenced by the main factors 'Storage time', 'Tomato cutting', and 'UV-C treatment', as well as their interactions, 'Storage time × Tomato cutting' and 'UV-C treatment × Tomato cutting'.

In whole tomatoes, TR_m was strongly affected by 'Storage time', 'UV-C treatment', and their interaction (P-value≤0.001) where 'UV-C treatment' had the highest F-Ratio=111.80. For fresh-cut tomatoes, both 'Storage time' (P-value≤0.001, F-Ratio=223.95) and 'UV-C treatment' (P=0.0373<0.05, F-Ratio=2.89) signifi-

Table 6: Transpiration rate (g_w kg^{-1} h^{-1}) of whole and fresh-cut tomatoes as affected by 'UV-C treatment'.

Treatment	Whole tomatoes	Fresh-cut tomatoes
Control	0.037 ± 0.02^a	1.096 ± 0.12^a
UV-C (0.22 kJ m^{-2})	0.102 ± 0.02^b	1.064 ± 0.12^a
UV-C (0.40 kJ m^{-2})	0.153 ± 0.02^c	0.958 ± 0.12^a
UV-C (1.23 kJ m^{-2})	0.255 ± 0.02^d	1.000 ± 0.12^a

Values with different superscripts within the same column are significantly different (P $\leq$ 0.05) according to Fisher's least significant difference (LSD) test.

Table 7: ANOVA of transpiration rate (g_w kg^{-1} h^{-1}) as affected by 'UV-C treatment', 'Tomato cutting', and 'Storage time.

Factor	*df*	F-Ratio	P-Value
A: UV-C treatment	3	2.87	0.0365*
B: Tomato cutting	1	2269.46	≤0.001*
C: Storage time (h)	4	269.39	≤0.001*
Interactions			
A×B	3	14.67	≤0.001*
A×C	12	1.17	0.3019^{NS}
B×C	4	161.33	≤0.001*
A×B×C	12	1.38	0.1753^{NS}

* = significant at P≤0.05; df=degree of freedom; All F-ratios are based on the residual mean square error, NS=not significant.

cantly affected TR_m. Temporal analysis revealed a declining trend in TR_m from 24 h onwards for fresh-cut tomatoes, as well as for whole tomatoes. In contrast, TR_m remained relatively stable in control tomatoes and 0.22 kJ m^{-2} treated whole tomatoes but significantly different among the different levels of UV-C doses (LSD=±0.012). These dynamics are regulated by the WVPD gradient, which drives water loss as the internal vapour pressure equilibrates with the ambient air. Therefore, the observed variations in TR_m over storage time and UV-C treatment, despite the identical storage conditions, are primarily dictated by fruit morphology, particularly the presence or absence of cuticular resistance.

4 Conclusion

This study, investigated the combined effects of UV-C irradiation, cutting status and storage time on the postharvest quality properties of whole and fresh-cut tomatoes. The findings indicate that UV-C treatment is effective in preserving the quality of whole tomatoes, notably through reductions in mass loss, enhanced firmness retention, stabilised colour characteristics and extension of shelf-life. In contrast, the application of UV-C irradiation on fresh-cut tomatoes produced mixed outcomes, primarily due to the higher surface exposure and absence of protective epidermal layers, which deteriorated moisture loss and oxidative stress, and accelerated ripening.

Colorimetric analysis revealed that fresh-cut tomatoes exhibited more pronounced changes in lightness, chroma and hue angle, especially at higher UV-C doses, suggesting increased pigment degradation and oxidative processes. Similarly, while UV-C treatment effectively preserved firmness in whole tomatoes, its effect on fresh-cut samples was limited, with a faster decline in texture integrity observed. Respiration and ethylene production rates were significantly higher in fresh-cut tomatoes, and further stimulated by UV-C treatment, pointing to enhanced metabolic activity and stress-induced ripening.

These results highlight the differential response of whole and fresh-cut tomatoes to UV-C irradiation. While whole tomatoes benefit from UV-C irradiation in terms of quality preservation and shelf-life extension, fresh-cut tomatoes require dose optimization to avoid quality degradation. Lower UV-C doses (0.22–0.40 kJ m^{-2}) appear to offer a compromise, maintaining quality properties without inducing excessive oxidative or ripening stress. However, further targeted research is necessary to refine UV-C treatment protocols, particularly for minimally processed tomatoes, considering varietal differences, ripeness stages, and exposure parameters.

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