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Ultraviolet-C light irradiation maintains the quality of chili (*Capsicum annuum L.*) during storage

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Abstract

The study aims to evaluate the effects of different doses of UV-C light treatment on the shelf life and quality of fresh chilies at two maturity stages. Fresh chilies were irradiated with ultraviolet-C (UV-C) light using doses of 0, 14, 24, 29, 47, 57, and 94 kJ/m², and then stored at 15°C for 12 days. The results indicated that UV-C light treatment at a dose of 14 kJ/m² positively impacted the quality and extended the shelf life of the chilies, resulting in an increase of 12 days for green chilies and 9 days for red chilies. This represents an extension of 6 days for green chilies and 3 days for red chilies compared to the control group. Additionally, the UV-C treatment at 14 kJ/m² demonstrated several benefits for both green and red chilies: (i) it inhibited weight loss and mold growth, (ii) reduced respiration rates and ethylene production, (iii) increased capsaicin levels, and (iv) helped maintain freshness.

Keywords: capsaicin; ethylene; freshness; respiration; weight loss

Introduction

Chili (*Capsicum annuum* L.) is an essential horticultural product and a popular culinary spice used worldwide. However, postharvest losses in fresh chilies are significant, primarily due to inadequate handling during transportation and storage (Munarso *et al.,* 2020). Chilies have high moisture content and respiration rates, making them susceptible to damage and resulting in a short shelf life (Chitravathi *et al.,* 2014; Maurya *et al.,* 2020). Typically, chilies have a shelf life of approximately 6 days after harvest (Anjayani and Ambarwati, 2021). This issue poses a serious challenge to the utilization and development of postharvest chili. Therefore, it is crucial to develop effective preservation technologies for fresh chili during storage.

One effective technology for maintaining the quality and extending the shelf life of horticultural commodities is the application of ultraviolet (UV) light irradiation (Darré *et al.,* 2022; Lante *et al.,* 2016; Yamaga *et al.,* 2016; Yemmireddy *et al.,* 2022). UV light is classified into three types: UV-A, which has a wavelength of 320–400 nm;

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UV-B, with a wavelength of 280–320 nm; and UV-C, ranging from 200 to 280 nm (Fonseca and Rushing, 2008). The application of UV-C irradiation is a straightforward postharvest handling method for fruits and vegetables. It meets the requirements for fresh food and has been approved by the Food and Drug Administration (FDA) (Fonseca and Rushing, 2006).

The UV-C light offers several mechanisms to enhance the quality and extend the shelf life of various horticultural commodities (Tripathi *et al.,* 2024; Qasem *et al.,* 2024). It helps prevent damage by boosting tolerance to pests and diseases, increasing the activity of defense enzymes, inhibiting bacterial growth, and inducing the expression of disease-resistance genes (Charles *et al.,* 2009, 2008a, 2008b, and 2008c). Additionally, UV-C light has antimicrobial properties (Artés *et al.,* 2009) and suppresses the expression of genes linked to maturity and senescence (Pombo *et al.,* 2009). Furthermore, it enhances secondary metabolism (Rodoni *et al.,* 2012) and improves the antioxidant status of fruits and vegetables (Jiang *et al.,* 2010). However, research on the application of UV-C light in the postharvest treatment of fresh chilies is still limited. This study aims to evaluate the effects of different doses of UV-C light treatment on the shelf life and quality of fresh chilies at two maturity stages. The results of this study are expected to contribute to maintaining the postharvest quality and extending the shelf life of fresh chilies.

Methodology

Plant materials

The fresh chilies cv. TW (*Capsicum annuum* L) were obtained from farmers' gardens at an altitude of 200 m above sea level (60.21°E, 106.44°S) in Ciherang, Dramaga Village, Bogor district, West Java province, Indonesia, and transported immediately to the laboratory. Chilies were harvested at green-ripe (green) and fully ripe (red) stages. The characteristics of different maturity stages are given in Table 1. Chilies were sorted and selected based on uniform size; only chilies without any physical defects were picked.

UV-C light treatment and storage condition

The sorted chilies, both green and red, of the variety TW (*Capsicum annuum* L), were placed in a UV-C chamber unit measuring 23 × 18 × 43 cm, which was equipped with a reflector. The chilies were positioned at two distances: 15.5 and 30 cm, corresponding to UV-C light intensities of 0.133 and 0.218 mW/cm², respectively. The exposure duration to UV-C light was set at 0, 3, 6, and 12 h. Each chili was manually rotated thrice to ensure even exposure of the surface to UV light. The dose of UV-C light (measured in kJ/m²) was calculated by multiplying the intensity of the UV-C light by the exposure time in seconds. This resulted in seven treatment levels of UV-C doses: 0, 14, 24, 29, 47, 57, and 94 kJ/m² (Table 2). Previous research (Rodoni *et al.,* 2012) indicates that a UV-C dose of 20 kJ/m² effectively reduces chili damage, with a trend showing that the deterioration index decreases with higher doses of UV-C light. Therefore, in this study, both low and high (extreme) doses of UV-C treatment were applied.

The refrigerator is a two-door model, specifically the RT9M300BGS, operating at a power of 220V/9Hz. It features a compressor identified as NC4AV80ALR/TT4 and has the model code RT19M300BGS/SE03. This unit has been modified to function as a UV-C sterilizer. The irradiation chamber is lined with aluminum foil to ensure even distribution of UV-C rays, as aluminum foil effectively reflects these rays. The refrigerator is equipped with two UV-C lamps, each rated at 10 watts, providing a total output of 20 watts.

The application of UV-C irradiation on fresh chilies in this study is illustrated in Figure 1. Each UV-C treatment was conducted on chilies at two maturity stages—green and red—with two replications for each stage. Each replication consisted of 10 bags, divided into 5 for destructive analysis and 5 for nondestructive analysis, resulting in 280 bags needed for both maturity stages. The replications were organized based on harvest time, with the first and second replications spaced 14 days apart. UV-C irradiation was performed at temperatures ranging from 18 to 20°C.

After UV-C irradiation treatment, 50 g of chilies were placed in polyethylene (PE) bags measuring 16 × 8 cm with a thickness of 0.03 mm. Each bag had eight holes pricked for ventilation. The chilies were then stored at 15°C for 12 days. Chili samples were analyzed on Days 0, 3, 6, 9, and 12 for both destructive and nondestructive analyses. An overview of the study procedure is briefly outlined in Figure 2.

Table 1. Characteristics of chilies for two maturity stages.

Maturity stage	Surface color	Hue color value	Harvesting time after anthesis (days)
Green-ripe (green)	>95% of the fruit surface showing green color	103 ± 2	24 ± 1
Fully-ripe (red)	>95% of the fruit surface showing red color	53 ± 2	42 ± 1

Table 2. The UV-C light dose treatments during storage.

Duration of exposure to UV-C light		UV-C light intensity (mW/cm²)	Dose of UV-C light (kJ/m²)	Code of treatment
hours (h)	second (s)			
0	0	0.133	0	Control
3	10.800	0.133	14	D14
6	21.600	0.133	29	D29
12	43.200	0.133	57	D57
0	0	0.218	0	Control
3	10.800	0.218	24	D24
6	21.600	0.218	47	D47
12	43.200	0.218	94	D94

Weight loss

The weight loss in the chili was calculated using the method proposed by Arif *et al.* (2023). Weight loss measurements were carried out by comparing the weight difference at the end of each observation. Observations were made on Day 12. The weight of the chilies was determined by weighing the samples using digital scales. The weight loss was expressed in percentage.

Respiration rate and ethylene production

The respiration rate was measured based on the rate of CO_2 production by red and green chilies using the F-950

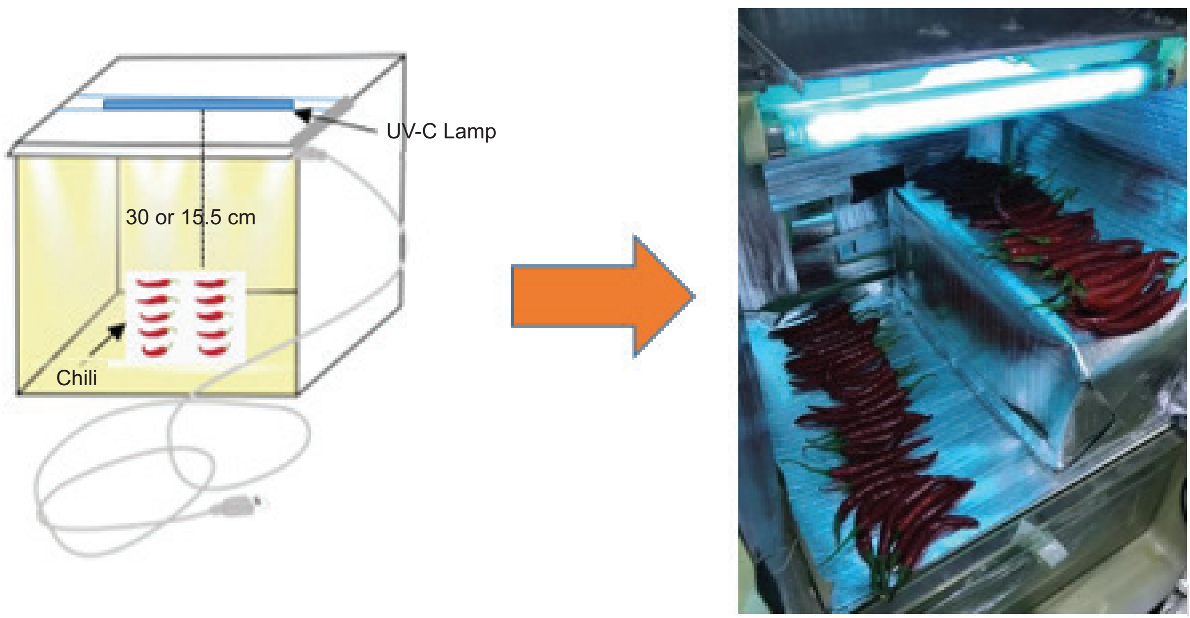

Figure 1. Illustration showing the application of UV-C irradiation on fresh chilies.

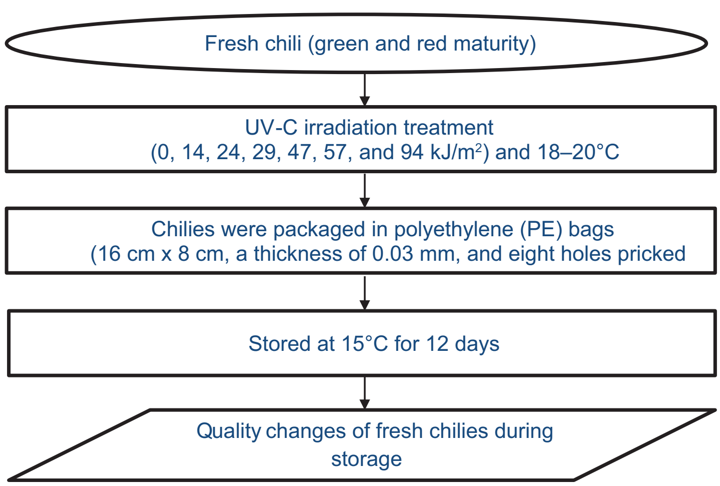

Figure 2. An overview of the study procedure.

Three Gas Analyzer. The weighed chili was put into the container and closed; the hole was connected to the outlet pipe and intake (Arif *et al.,* 2022; Susanto *et al.,* 2023). The chili from each bag sample was stored in a 2 L sealed glass bottle for 1 h at ambient temperature (28 ± 1°C and 80 ± 5% RH). Then, the glass bottles were transferred to a room at 23°C and 85% RH to measure respiration rate and ethylene production. These conditions were based on Felix's instrument, so the Gas Analyzer functions optimally. Measurements were done by opening the two valves of the sealed glass bottle and inserting them into the two interfaces of the Gas Analyzer to form a closed loop. After the digital display of the instrument was stable, the total amount of CO_2 and ethylene in the closed glass bottle was recorded, and the respiratory rate and ethylene production were calculated according to the measurement results. The respiration rate was expressed in mL/kg h, and ethylene production was expressed in μL/kg h.

Freshness and mold attacks

The freshness of chilies was observed by analyzing the green chili stalks, dense flesh, and their straight and not wilted appearance. Freshness analysis was observed based on the following values and criteria:

1 = Very wilted
2 = Wilted
3 = Fresh
4 = Very fresh

Moldy attacks were assessed visually and categorized as: – = no attacks; + = there are attacks.

Color

Two to three chili samples were taken, and their color was analyzed using a chromameter. The appearance of the values brightness (L*), redness (a*), and yellowness (b*) indicated the measurement results. From the values L*, a*, and b*, it could be seen that the hue angle (h*) was calculated using the following equation (Xiang *et al.,* 2000):

$$h^* = \arctan\left(\frac{b^*}{a^*}\right)$$

Ascorbic acid

Ascorbic acid was measured following the method suggested by Suriati *et al.* (2021). Five grams of chili sample was added to 25 mL of 0.5% phosphoric acid, stirred using an ultrasonic bath at 3000 rpm for 30 min, and filtered with a microfilter. The supernatants were analyzed using ultra-performance liquid chromatography (UPLC) Dionex Ultimate 3000 RS Column Compartment. Ascorbic acid was expressed as mg/100 g.

Total acidity and total soluble solids

Two grams of mashed chili was weighed and transferred into a 250 mL volumetric flask. Distilled water was added until the mark and shaken. The solution was filtered, and 25 mL was pipetted into a 100 mL Erlenmeyer flask, to which a few drops of phenolphthalein indicator were added. This was titrated against 0.1 N NaOH solution until it turned red (Maurya *et al.,* 2020).

$$\text{Total acidity (TA\%)} = \frac{\text{mL} \times \text{N} \times \text{FP} \times \text{BS}}{\text{mg samples}} \times 100\ \%$$

where, FP = Dilution factor; N = concentration of NaOH; and BS = molecular weight.

The total soluble solids (TSS) were measured using a refractometer with units of °Brix. The chilies were cleaned, crushed, and filtered to get chili juice. The results were recorded by placing one to two drops of the sample on the prism part of the tool. The prism of the refractometer was washed with 70% alcohol before and after use.

Capsaicin

The chili sample analyses were conducted using the method by Sharma *et al.* (2012) with some modifications. The chilies were cleaned and oven dried for 24 h at 65°C to decrease the moisture content, air dried at ambient temperature, and crushed with a blender (1–2 chilies). Two grams of chili sample were weighed and transferred into a 50 mL volumetric flask, to which 5 mL of acetone and 25 mL of ethanol were added. The chili tube was wrapped with aluminum foil until tightly closed and isolated from light. This was then ultrasonicated at 80°C for 4 h.

The sample was kept in an ultrasonicator bath at 3000 rpm for 30 min and stored in the refrigerator for 24 h at 5°C. The sample was first filtered using Whatman filter paper 22 μm and again using a 0.45 m syringe, and this was poured into the HPLC sample vial (tube vial) using a 0.5 mL HPLC syringe. This study utilized a type C-18 column (Agilent Eclipse Plus C18, 5 m, 4.6 × 250 mm) with a flow rate (FR) of 1 mL/min and retention time of (RT) 15 min at 60°C. The HPLC used was Thermo Scientific Ultimate 3000.

Statistical analysis

Data were reported as mean ± SD. The data were subjected to analysis of variance, and the mean values were compared using Duncan Multiple Range Test (DMRT). All tests were considered significant at $P < 0.05$.

Results and Discussion

Weight loss, respiration rate, and ethylene production

Weight loss is one of the factors that determines the quality of chili. Weight loss is a decrease in product weight due to the loss of water content. Weight loss is related to transpiration and respiration rates, which affect the quality of horticultural commodities (Arif *et al.,* 2022, 2023; Susanto *et al.,* 2023). The greater the weight loss in chili, the lower the quality (Hameed *et al.,* 2013). The weight loss in chili at both maturity stages during storage increased with increasing doses of UV-C light (Figure 3). The increased weight loss in red chili was higher than that of green chili. The results of this study also showed that low-dose UV-C application maintained weight loss during storage. On Day 12 of storage, the weight losses in the UV-C irradiation treatment at a dose of 14 kJ/m^2 were 7.32 and 12.30% for green and red chilies, respectively, while those of the controls for green and red chilies were 3.55 and 3.47%, respectively (Figure 3). Tripathi *et al.* (2024) reported that exposing mung bean sprouts to UV-C light during a storage period of up to 6 days effectively prevented weight loss and helped maintain their firmness. Similarly, Duarte-Sierra *et al.* (2019) reported that broccoli treated with UV-C exhibited less weight loss than samples that were not treated with UV-C.

Weight loss in fresh fruits and vegetables is primarily due to water loss caused by transpiration (Yang *et al.,* 2015). The increase in chili weight loss with increasing doses of UV-C light can be affected by changes in the permeability of fruit skin tissue. Hosseini *et al.* (2019) stated that UV-C irradiation effectively reduces microbial growth, minimizes tissue damage and weight loss, and maintains product firmness. Artes-Hernandes *et al.* (2009) stated that UV-C could change cell permeability in leafy vegetables. Lower weight loss due to UV-C is associated with the formation of a thin film on the product's surface, inhibiting water evaporation in fresh-cut apples (Manzocco *et al.,* 2011). The modifications in UV-C-treated cells

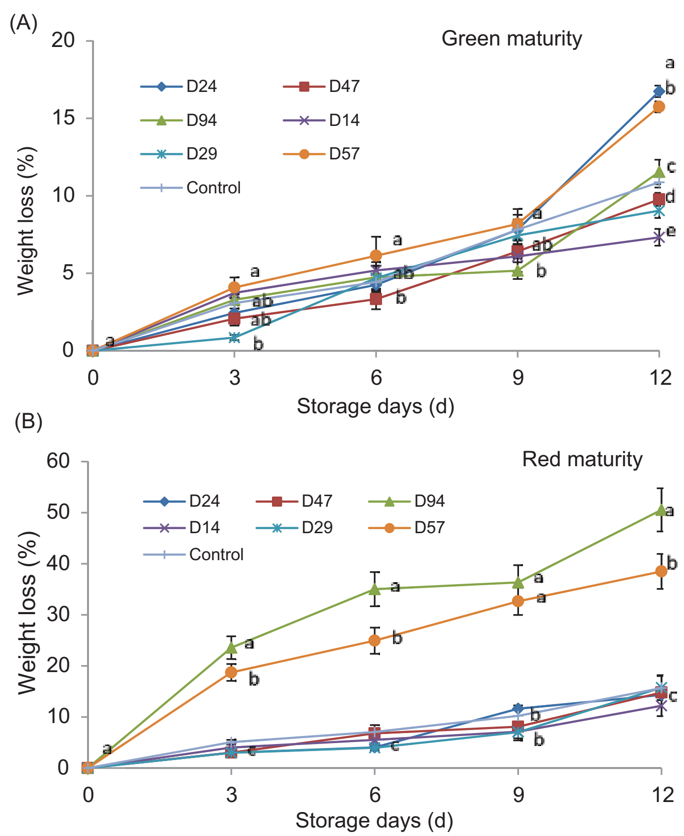

Figure 3. Effect of UV-C light treatments with different concentrations on weight loss of (A) green chili; and (B) red chili during storage. Different letters on the same day indicate the significant difference by Duncan multiple range test (P < 0.05).

could be partially ascribed to the breakage of apples' cellular membranes, which would cause a loss of functional cell compartmentalization. These effects were attributed to the direct inactivation of spoilage microorganisms and enzymes by UV-C light, and it caused the formation of a thin, dried film on the product's surface (Manzocco *et al.*, 2011). In addition, UV irradiation can affect the rate of water loss, including changes in surface wax deposition (Charles *et al.*, 2008a) or modifications to the degree of stomata closure (He *et al.*, 2011). Considering the lower weight loss in the UV-C treatment of 14 kJ/m^2 on green and red chilies during storage, this treatment was considered a method that inhibited weight loss.

The respiration rate of chilies showed a tendency to increase during storage in all treatments (Figure 4). Even though chilies have a non-climacteric ripening pattern on respiration, previous studies have reported that CO_2 production can increase, especially after long-term storage (Marni *et al.*, 2020). This increase is mainly related to prolonged stress conditions in the postharvest environment, such as water and nutrient shortage and pathogen challenges that can cause damage to the fruit (Li and Kader, 1989). In the current study, the UV-C treatment of 14 kJ/m^2 showed lower CO_2 production compared to other treatments during storage for green and red chilies (Figure 4). Given that chili is a non-climacteric fruit, increased CO_2 production seems more likely to be related to spoilage as the fruit approaches senescence. In this scenario, the lower respiration of the chilies treated with UV-C treatment of 14 kJ/m^2 could be interpreted as a delay in tissue disruption. Furthermore, the respiration rate continued to rise with higher doses of UV-C light (greater than 14 kJ/m^2). The heat produced by the UV-C light can elevate the storage temperature, significantly impacting the product's respiration rate. Thus, it suggests that the UV-C treatment at 14 kJ/m^2 reduces damage to chili pods and may help maintain lower metabolic activity.

Ethylene is an active hormone that plays a significant role in the growth process of plants. Chili is a non-climacteric fruit. Ethylene production in non-climacteric fruits tends to be in basal conditions without any environmental changes or exposure to stress, which encourages increased ethylene production in fruits and vegetables (Brecht, 2019). Consistently, UV-C irradiation also induced more ethylene production than green and red chili controls (Figure 5). Higher ethylene production in untreated chilies and those treated with high doses of UV-C was associated with senescence, resulting in faster deterioration of physical characteristics (Pristijono *et al.*, 2019). The use of UV-C light with high doses is thought to cause an increase in voltage due to the heat generated

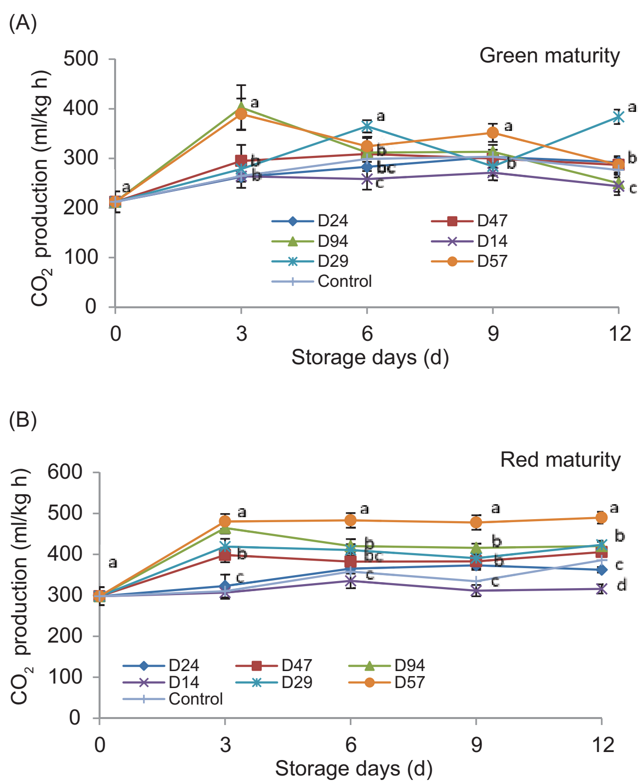

Figure 4. Effect of UV-C light treatments with different concentrations on CO_2 production of (A) green chili; and (B) red chili during storage. Different letters on the same day indicate the significant difference by Duncan multiple range test (P < 0.05).

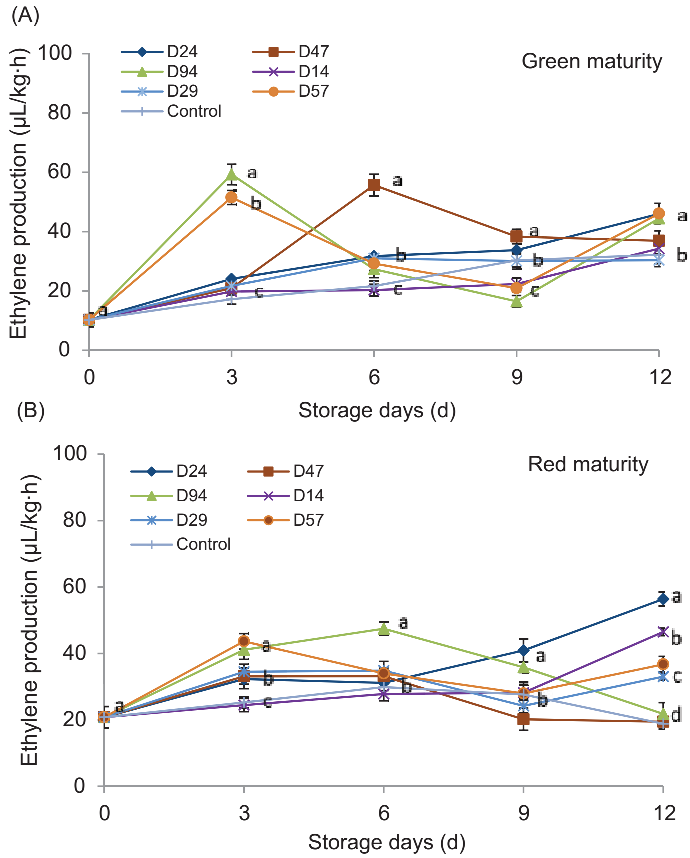

Figure 5. Effect of UV-C light treatments with different concentrations on ethylene production of (A) green chili; and (B) red chili during storage. Different letters on the same day indicate the significant difference by Duncan multiple range test ($P < 0.05$).

by the UV-C light, thereby increasing the temperature of the storage environment. Temperature is a factor that significantly affects the rate of ethylene production. Nakano *et al.* (2001) stated that high doses of UV-C treatment could stimulate ethylene production in persimmons. Civello *et al.* (2014) stated that abiotic stress (heat, injury, and oxidative stress) increases ethylene production. UV radiation is a strong oxidant that can enhance ethylene biosynthesis in plant tissues.

Freshness and mold attack

Most Indonesian households primarily demand fresh chilies, making data on their freshness crucial for ensuring quality during storage. Table 3 presents findings on the freshness of chilies subjected to various UV-C irradiation treatments. After 12 days of storage, red chilies exhibited more damage than green chilies (Table 3 and Figure 6). This is likely due to the higher water content in red chilies, which allows for a greater presence of microorganisms. However, the UV-C treatment effectively preserved the freshness of green chilies, achieving a freshness score of 3 after 12 days at 15°C (Table 3). The UV-C treatment significantly delayed fungal infections on green chilies, with mold appearing 6 days later than in the control (Table 3). While there was no significant difference in overall freshness between red and green chilies (Table 3), the former suffered more physical damage, particularly from mold attack. For UV-C-treated red chilies, mold infestations started on Day 9 of storage, which was 3 days later than in the control (Table 3). This study indicates that UV-C light can effectively suppress mold attacks on chilies. By enhancing disease tolerance and inhibiting mold growth, UV-C light helps reduce damage (Charles *et al.,* 2008a, 2008b, 2008c, and 2009). Additionally, UV-C light has antimicrobial properties (Artés *et al.,* 2009; Phornvillay *et al.,* 2022), stimulates secondary metabolism (Rodoni *et al.,* 2012), and improves the antioxidant status in fruits and vegetables (Jiang *et al.,* 2010). Among the treatments tested, the 14 kJ/m^2 UV-C treatment was the most effective in maintaining freshness and inhibiting mold growth in both green and red chilies during storage.

Color

Color is the primary quality parameter for selecting chilies, as it can be visually observed. The color change

Table 3. Freshness and mold attacks scoring in chilies with different doses of UV-C light during storage.

Treatments		Freshness					Mold attacks				
Maturity	UV-C	Day 0	Day 3	Day 6	Day 9	Day 12	Day 0	Day 3	Day 6	Day 9	Day 12
Green	D14	4 ± 0	4 ± 0	4 ± 0	3 ± 0.0	3 ± 0.0	–	–	–	–	–
	D24	4 ± 0	4 ± 0	4 ± 0	3 ± 0.0	3 ± 0.0	–	–	–	–	+
	D29	4 ± 0	4 ± 0	4 ± 0	3 ± 0.0	3 ± 0.0	–	–	–	–	–
	D47	4 ± 0	4 ± 0	4 ± 0	4 ± 0.0	3 ± 0.0	–	–	–	–	–
	D57	4 ± 0	4 ± 0	4 ± 0	3 ± 0.0	3 ± 0.9	–	–	–	–	+
	D94	4 ± 0	4 ± 0	4 ± 0	3 ± 0.9	3 ± 0.9	–	–	–	–	+
	Control	4 ± 0	4 ± 0	4 ± 0	3 ± 0.9	3 ± 0.9	–	–	+	+	+
Red	D14	4 ± 0	4 ± 0	4 ± 0	3 ± 0.0	3 ± 0.0	–	–	–	+	+
	D24	4 ± 0	4 ± 0	4 ± 0	3 ± 0.0	3 ± 0.0	–	–	–	+	+
	D29	4 ± 0	4 ± 0	4 ± 0	3 ± 0.0	3 ± 0.0	–	–	–	+	+
	D47	4 ± 0	4 ± 0	4 ± 0	3 ± 0.0	3 ± 0.9	–	–	–	+	+
	D57	4 ± 0	4 ± 0	4 ± 0	3 ± 0.0	2 ± 0.0	–	–	–	+	+
	D94	4 ± 0	4 ± 0	4 ± 0	3 ± 0.9	3 ± 0.9	–	–	–	–	+
	Control	4 ± 0	4 ± 0	4 ± 0	3 ± 0.9	3 ± 0.9	–	–	+	+	+

–, no attacks; +, attacks present.

is visible in fruit ripening due to the synthesis of certain pigments, such as carotenoids and flavonoids, in addition to chlorophyll degradation. The color changes in chilies after UV-C light treatment were evaluated by calculating the hue angle, which indicates the dominant color. The hue angle value of green chili decreased with increasing doses of UV-C lights during storage (Figure 7). The low hue angle value indicated less green peel of green chili, which is thought to be related to chlorophyll levels. Ebrahimi *et al.* (2024) reported that UV light treatment can effectively remove chlorophyll from plant extracts without adversely affecting their antioxidant activity in food systems. Imaizumi *et al.* (2018) also reported that cucumbers treated with UV-C showed a decrease in chlorophyll content during storage. Chili and cucumber are non-climacteric vegetable products, so the decrease in chlorophyll content is associated with the senescence of the product.

On the other hand, the red chili exhibited fluctuating hue angle values ranging from 36 to 60° (Figure 7), showing little change at higher UV-C doses. However, visual observations indicated that the physical appearance of the chilies shifted slightly from red to yellowish-red at these higher UV-C doses, although this change was not significant. Hosseini *et al.* (2019) noted that a decrease in color indices (L*, a*, and b*) signifies the decomposition of anthocyanin pigments. Anthocyanins are phenolic compounds responsible for the red color in some fruits and vegetables. The degradation of these compounds, influenced by internal and external factors, can diminish color-related quality indicators. Irradiation leads to water radiolysis, producing free radicals that degrade anthocyanin by disrupting the ring structure and producing colorless chalcones (Lee *et al.,* 2011). Changes in the negative direction of a* and hue indicate the darkening of the fresh chili surface. The decrease in a* values in irradiated samples can be attributed to anthocyanin degradation (Alighourchi *et al.,* 2008). In this study, UV-C light doses between 14 and 24 kJ/m² are recommended to help maintain the hue angle value during the storage of red chilies.

Ascorbic acid and total acidity

Ascorbic acid is recognized as a natural antioxidant that can detoxify reactive oxygen species (ROS) and hydrogen peroxide (H_2O_2) (Luengwilai *et al.,* 2018). Table 4 shows the ascorbic acid content in chilies treated with UV-C light at various doses after 12 days of storage. The doses of UV-C light applied affect the ascorbic acid levels in the chilies. Specifically, UV-C treatment resulted in the reduction of ascorbic acid content compared to untreated chilies (the control), affecting both green and red maturity. Maharaj *et al.* (2014) observed that the ascorbic acid content in tomatoes was higher in the exocarp of untreated samples compared to those treated with UV-C. The decrease in ascorbic acid content in chilies subjected to UV-C treatment is attributed to the oxidation of ascorbic acid, which is influenced by the availability of oxygen, high temperatures, and pH levels. Additionally, Gonzales-Aguilar *et al.* (2007) found that the ascorbic acid content in

Figure 6. Images of fresh chilies on Day 12 of storage.

fresh-cut mangoes exposed to UV-C light decreased due to the oxidation of ascorbic acid, which increased with longer UV-C exposure times.

The TA of green chili after 12 days of storage ranged from 0.030 to 0.175%, while that of red chili ranged from 0.030 to 0.069% (Table 4). In both maturities of chili, exposure to UV-C light significantly increased the TA acidity compared to the control. The UV-C dose also affected the TA, with the highest TA observed in mangoes treated with the highest UV-C dose to be 11.7 kJ/m^2 (Pristijono *et al.,* 2019). Similarly, higher TA has been reported in UV-C irradiated peaches (Abdipour *et al.,* 2019) and cherry tomatoes (Razali *et al.,* 2021). The use of UV-C light on chilies prevents microbial growth, which in turn reduces acid production. Pan and Zu (2012) noted that low levels of TA may result from UV-C treatment, as it can decrease the number of microorganisms present in the product. UV-C treatment at varying doses can also inhibit respiration compared to the control, specifically at doses 57 and 94. This inhibition suggests that UV-C treatment helps prevent the breakdown of organic acids into sugars and energy during respiration. During storage, fruits typically convert organic acids into sugars and energy for survival (Arif *et al.,* 2023; Susanto *et al.,* 2023). Consequently, the lower respiration rate associated with low-dose UV-C treatment helps maintain higher TA levels than the control and higher-dose UV-C treatments.

Total soluble solids and capsaicin

The TSS content of green chili ranged from 4.1 to 6.5 °Brix, while that of red chili ranged from 8.1 to 9.5 °Brix (Table 4). The TSS of red chili is greater than that of green chili due to the differences in the maturity stages of the chilies. Starch conversion occurs in the plant during fruit ripening, resulting in a higher TSS in red chili. According to Villa-Rivera and Ochoa-Alejo (2021), plant fruit ripening involves physiological and biochemical transformation processes that are genetically regulated and occur in the final stages of fruit development. In addition, in this study, chilies harvested at the red maturity stage may have contributed to the minimal effect of UV-C on TSS. The red chili undergoes a biochemical process and accumulates all the sugars, which causes a difference in TSS content of about one °Brix, which may not affect consumer preferences.

The TSS of green chili increased with a UV-C dose of 47 kJ/m^2 but decreased with higher UV-C doses. In contrast, the lowest TSS for red chili was observed at UV-C doses of 14 and 57 kJ/m^2. The hydrolysis of starch increases sugar content, as higher UV-C doses convert starch into sucrose, glucose, and fructose more quickly than glucose is converted into energy and water. This results in the accumulation of sugars in the tissues during storage (Wills *et al.,* 1997). Additionally, starch hydrolysis is linked to the respiration rate; a slower respiration rate indicates a delay in the breakdown of starch and organic acids into sugars. Therefore, a UV-C dose of 14 kJ/m^2 is recommended for both stages of chili maturity (green and red), as this dose tends to result in lower TSS levels compared to other treatments. This finding is also supported by the observation of a slower respiration rate, which contributes to a longer shelf life.

The capsaicin content in green chili ranges from 3.6 to 844.1 ppm, while that in red chili ranges from 4.8 to 3252.4 ppm after 12 days of storage (Table 4). Red chili has a higher capsaicin content than green chili; generally, the riper the fruit, the greater the level of spiciness (capsaicin). According to Villa-Rivera and Ochoa-Alejo (2021),

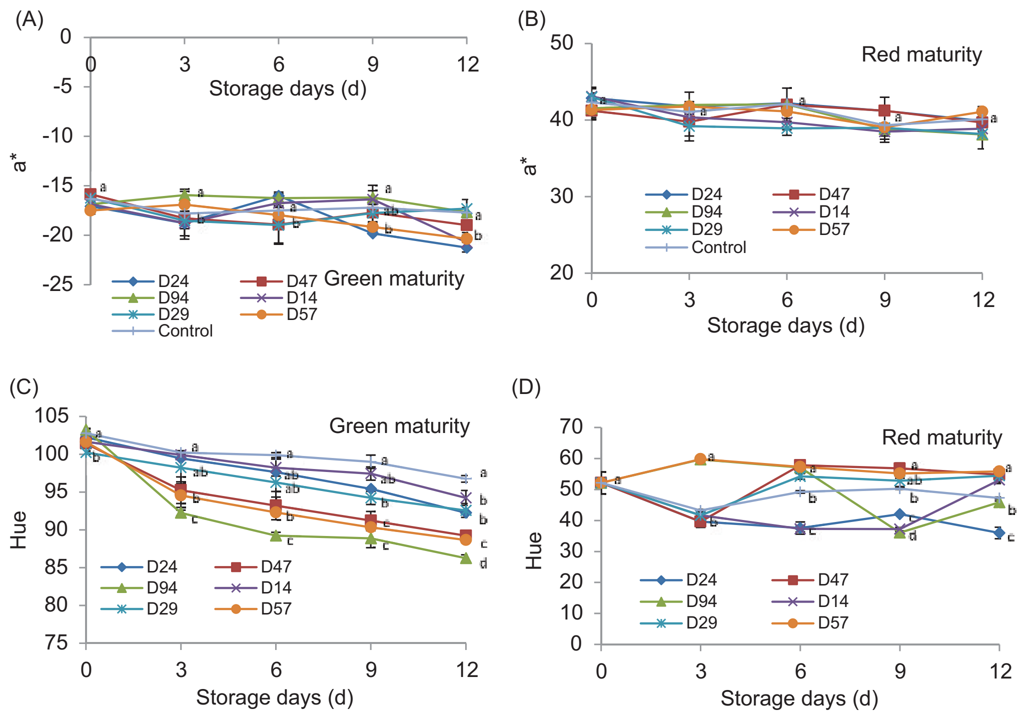

Figure 7. Effect of UV-C light treatments with different concentrations on a* of (A) green chili, and (B) red chili, and hue of (C) green chili, and (D) red chili during storage. Different letters on the same day indicate the significant difference by Duncan multiple range test (P < 0.05).

Table 4. Ascorbic acid, TA, TSS and capsaicin content in chilies with different doses of UV-C light after storage for 12 days.

Treatments		Ascorbic acid (mg/100 g)	TA (%)	TSS (°Brix)	Capsaicin (ppm)
Maturity	UV-C				
Green	D14	3.88 ± 0.37[c]	0.175 ± 0.015[a]	4.5 ± 0.3[c]	733.8 ± 267.8[a]
	D24	5.15 ± 0.45[b]	0.038 ± 0.004[c]	4.1 ± 0.2[c]	844.1 ± 386.4[a]
	D29	5.45 ± 0.43[b]	0.038 ± 0.003[c]	5.1 ± 0.2[b]	373.1 ± 121.4[a]
	D47	5.10 ± 0.37[b]	0.038 ± 0.004[c]	6.5 ± 0.9[a]	92.9 ± 65.3[b]
	D57	4.98 ± 0.34[b]	0.053 ± 0.005[b]	4.2 ± 0.3[c]	34.3 ± 23.5[b]
	D94	4.97 ± 0.37[b]	0.038 ± 0.002[c]	4.1 ± 0.4[c]	42.9 ± 21.7[b]
	Control	7.15 ± 0.49[a]	0.030 ± 0.003[c]	4.3 ± 0.5[c]	3.6 ± 1.6[c]
Red	D14	5.04 ± 0.58[c]	0.046 ± 0.012[b]	8.7 ± 0.3[b]	3249.4 ± 279.2[a]
	D24	6.32 ± 0.41[b]	0.069 ± 0.009[a]	9.3 ± 0.2[a]	3039.9 ± 101.4[a]
	D29	6.38 ± 0.37[b]	0.061 ± 0.007[a]	9.5 ± 0.3[a]	2942.0 ± 145.7[a]
	D47	6.11 ± 0.23[b]	0.046 ± 0.011[b]	9.3 ± 0.2[a]	2551.2 ± 172.5[b]
	D57	4.52 ± 0.51[c]	0.038 ± 0.004[c]	8.1 ± 0.4[b]	3252.4 ± 324.5[a]
	D94	5.20 ± 0.64[c]	0.038 ± 0.003[c]	9.5 ± 0.4[a]	2601.1 ± 113.2[b]
	Control	10.32 ± 1.33[a]	0.030 ± 0.009[c]	9.4 ± 0.2[a]	4.8 ± 1.8[c]

The numbers followed by the same letter in the same column indicate no significant difference by Duncan multiple range test (P < 0.05).

capsaicin accumulation in chili is genetically determined and varies based on developmental stage. Capsaicin accumulates in the fruit shortly after pollination (around 10 days) and continues as growth progresses, reaching maximum concentrations depending on the specific cultivar.

Table 4 also indicates that as the UV-C dosage increases, the capsaicin content in green chili decreases. A similar trend is observed in red chili. The optimal capsaicin content for green chili was achieved at a UV-C light dose of 14–24 kJ/m², while for red chili, the best results were observed at a dose of 14–29 kJ/m², as this range produces the highest spiciness. Notably, there was a significant increase in capsaicin content in red chili across all UV-C treatments. This phenomenon is likely due to the conversion of certain capsaicinoids, specifically capsaicate, which is sweet and abundant in chili, transforming into the hotter capsaicin. Capsaicin not only imparts spiciness to chilies but also possesses antioxidant properties. In this study, the increase in capsaicin due to UV-C treatment suggests that this compound plays a role in protecting chilies from oxidative stress or preventing tissue damage. Oxidative damage can be assessed through lipid peroxidation, where increased levels of malondialdehyde (MDA) indicate oxidative damage caused by UV-C, disrupting the cell defense system (Barka *et al.,* 2000; Costa *et al.,* 2002; Mahdavian *et al.,* 2008). Additionally, it was observed that UV-C light enhances total capsaicin at lower irradiation times, although this positive effect diminishes with higher UV-C light treatments (Pérez-Ambrocio *et al.,* 2018).

Practical implications

The current study confirms that exposure to UV-C light has a positive impact on the quality and shelf life of fresh chili peppers. As a result, UV-C light can be utilized in the chili industry to extend product freshness. This technique can enhance the shelf life of fresh chili while preserving its quality. The findings of this research are significant because they highlight the complexity involved in selecting the right technology to enhance shelf life and maintain the quality of fresh chili at the appropriate stage of maturity. Stakeholders in the chili industry should consider these findings to determine the ideal UV-C dosage and the optimal harvest maturity stage. This approach will help satisfy consumer preferences while also supporting the interests of chili farmers. Moreover, farmers, intermediary traders, wholesalers, supermarkets, and exporters can apply UV-C technology in their efforts to preserve chili. To ensure its effectiveness, it is important to design an applicator that accounts for the correct dosage, temperature, and reflection of UV-C light.

Conclusions

The findings of our study indicate that UV-C light treatment at a dose of 14 kJ/m² positively impacts the quality and shelf life of green and red chili, extending their freshness by 12 and 9 days, respectively. This treatment inhibits weight loss and mold growth, reduces respiration rates and ethylene production, increases capsaicin contents, and maintains freshness. Consequently, UV-C treatment at this dosage emerges as an effective method for prolonging shelf life and preserving the quality of chili, making it a valuable technique for the chili industry. This approach can enhance the shelf life of fresh chili while ensuring quality. The results of this study are significant as they underscore the complexities involved in selecting the appropriate technology to extend the shelf life and maintain the quality of fresh chili at the right stage of maturity. By doing so, this technology can better meet consumer preferences while supporting the interests of chili farmers. Moreover, this technology can benefit various stakeholders, including farmers, intermediaries, wholesalers, supermarkets, and exporters, in preserving fresh chili. However, further study is essential to confirm its effectiveness. It is also vital to design UV-C applicators for industrial use, considering factors such as the quantity of fresh produce, temperature, and proper reflectance of UV-C light.

Competing Interests

The authors had no relevant financial interests to disclose.

Authors' Contributions

All authors contributed equally to this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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