International Food Research Journal 28(1): 207 - 216 (February 2021)
Journal homepage: *http://www.ifrj.upm.edu.my*

Reduction of enzymatic browning of fresh-cut Chinese yam (*Dioscorea opposita*) by UV-C treatment

[1,2]Zhao, L., [1]Zhao, X., [1]Ma, Y., [3]Zhang, Y. and [1]*Wang, D.

[1]Beijing Vegetable Research Centre, Beijing Academy of Agriculture and Forestry Sciences, Beijing Key Laboratory of Agricultural Products of Fruits and Vegetables Preservation and Processing, Key Laboratory of Vegetable Postharvest Processing, Ministry of Agriculture and Rural Affairs, Beijing 100097, China
[2]Zhang Zhongjing College of Chinese Medicine, Nanyang Institute of Technology, Changjiang Road 80, Nanyang 473004, Henan, China
[3]Longda Food Group Co. Ltd., Shandong 265231, China

Article history

Received: 25 November 2019
Received in revised form: 10 May 2020
Accepted: 9 October 2020

Keywords

fresh-cut Chinese yam, UV-C treatment, enzymatic browning, microbial growth

Abstract

Herein, we studied the effect of UV-C (shortwave ultraviolet) irradiation on the quality and inhibition of the browning of fresh-cut Chinese yam (*Dioscorea opposita*). The irradiation of 0, 4, 8, 12, and 24 kJ m^{-2} were applied to fresh-cut Chinese yam, and quality characteristics were evaluated during 16 days of storage at 4°C. The results indicated that UV-C treatment (8 KJ m^{-2}) effectively decreased the browning degree, polyphenol oxidase (PPO) and peroxidase (POD) activities, and total bacteria count (TBC). However, the phenylalanine ammonia lyase (PAL) activity, PAL gene expression, respiration rate, and total phenol content increased. The UV-C treatment of 8 kJ m-2 resulted in a lower degree of membrane damage, as evidenced by the lower soluble quinone accumulation and browning index (BI), and retained the soluble solid content and hardness during storage. Increasing irradiation intensity would enhance cell damage while did not reduce browning. The results also showed that UV-C treatment alone had great potential to inhibit the browning of fresh-cut vegetables.

Introduction

Over the past few decades, the demand for fresh, healthy, and convenient foods such as fresh-cut Chinese yam had grown tremendously following lifestyle changes (Tadeo *et al.,* 2018; Tao *et al.,* 2019). However, tissue browning limits the shelf-life of fresh-cut vegetables and yams, and reduces their marketability as the off-colour could easily be detected, thus leading to refusal by consumers (Kan *et al.,* 2019; Bourneow and Toontam, 2019). The browning of Chinese yam is caused by a quinone product formed by phenolic acid substrate catalysed by enzymes and oxygen (Luo *et al.,* 2015), which is similar to other vegetables (Coelho Júnior *et al.,* 2018).

Currently, there are various preventive measures that are being applied to protect fresh-cut Chinese yam from browning and microbial infection, including chelation agent, antioxidant, and enzyme inhibitor treatments (high concentration of ethanol containing star anise essential oil, electrolysis oxidising water, and ethanol combined with ascorbic acid) (Jia *et al.,* 2015; Teoh *et al.,* 2016; Homaida *et al.,* 2017; Zhang *et al.,* 2019); ethanol fumigation treatment (Fan *et al.,* 2017); and physical processing method (ultra-high pressure, UV-C combined with ascorbate and calcium chloride) (Li *et al.,* 2016).

As a good way to maintain the appealing quality of postharvest fruits and vegetables, UV-C processing has the characteristics of low equipment cost, simple application, and no additional chemicals (Zhang and Jiang, 2019). Moreover, suitable dose of UV-C treatment could also promote fresh-cut fruits or vegetables to produce antioxidant secondary metabolites (such as phenolics) through oxidative stress (Li *et al.,* 2019a). Teoh *et al.* (2016) had studied UV-C irradiation combined with ascorbic acid and calcium chloride dips on the enzymatic activities and total phenolic content (TPC) of minimally processed yam (*Dioscorea* sp.) slices (Li *et al.,* 2016). However, the application of UV-C processing alone in fresh-cut vegetables is still rare. Furthermore, common fresh-cut yam varieties such as *Dioscorea alata, D. opposita,* and *D. rotundata* significantly vary in the activities of total phenolics, polyphenol oxidase (PPO), peroxidase (POD) activities, and phenylalanine ammonia lyase (PAL) (Hamon and Toure, 1990).

The Chinese yam (*D. opposita*) contains high polysaccharides, nutrients, and medicinal values (Ma *et al.,* 2005), and is more popular among the Chinese people (Song *et al.,* 2016) than other yam varieties (*Dioscorea* spp.) (Li *et al.,* 2016). Due to the difference

*Corresponding author.
Email: wangdan@nercv.org

DOI: https://doi.org/10.47836/ifrj.28.1.21

in total phenolic content and enzyme activity (PPO, POD, and PAL) associated with browning between Chinese yam (Luo *et al.,* 2015) and yam in the literature (*Dioscorea* spp.) (Li *et al.,* 2016), there should be different ways to inhibit browning. Furthermore, the effect of UV-C treatment alone on the quality of fresh-cut Chinese yam, especially browning, has not been studied thus far.

The present work was therefore designed to investigate the inhibition mechanism of browning of fresh-cut Chinese yam by UV-C treatment on membrane damage, browning-related enzyme activity, and PAL gene expression. The results confirmed the possibility of applying UV-C radiation alone to fresh-cut vegetable processing.

Materials and methods

Sample preparation

Commercial Chinese yams of "Tiegun" variety were purchased from a supermarket (Guoxiangsiyi, Zhanghua road, Beijing, China) and used for the experiment following preservation for 24 h at 4°C. Fresh samples at similar maturity stage were randomly selected, and examined to be free from defects and mechanical damages. The samples were washed under running tap water, peeled, and cut into slices of 5 mm thickness.

A bout 1000 g of fresh-cut Chinese yams were immersed into 100 and 50 mg/L of sodium hypochlorite solutions at pH 6.5 for 2 min (Raseetha and Nadirah, 2018). After dehydration, about 120 g of slices were randomly packaged in plastic bags (PE, 4.25 μm thick, and 41 cm × 29 cm dimension), and stored at 4°C. Oxygen and carbon dioxide transmission rates of PE bags were 1541.25 and 5749.39 cm^3/m^2•24 h•0.1 MP, respectively.

UV-C equipment and treatment incubation conditions

The radiation chamber consisted of two groups of lamp tubes (one group installed horizontally above the Chinese yams, and the other one underneath them), and each group had three UV-C bulbs (TUV 36W/G36 T8, Philips, Beijing, China) with the wavelength of 254 nm. The vertical distance between the lamps and the samples was 45 cm. Short-wave UV radiation intensities were measured by a radiometer (LS-125, Linshang, Shenzhen, Guangdong) placed in the same location as that of fresh-cut Chinese yam samples.

Adjustment of irradiation intensities was done by changing the irradiation time at a fixed dose and area, to ensure that every Chinese yam slice was irradiated. The applied irradiation was CK: non-irradiated samples; and the UV-C irradiation doses in the packaging bags were as follows: 0, 4, 8, 12, and 24 kJ/m^{-2}.

Three replicates were performed for each treatment, and measurements followed the completely randomised design. Samples were stored at 4°C and 80 - 85% humidity for 16 d, in a constant temperature inside a humidity box (QL, HWHS). The quality characteristics of samples were determined on days 0, 4, 8, 12, and 16.

Microbiological analysis

Fresh-cut Chinese yam slices (25 g) from each package were immersed and mixed with 225 mL aseptic NaCl solution (0.85%) for 25 min, and then, 1 mL of solution were plated onto Nutrient agar. Agar plates were incubated at 37°C for 48 h. The microbiological analysis was performed following the method of Jamesa *et al.* (2010). Microbial data are represented by logarithmic values for analysis, and performed on days 0, 4, 8, 12, and 16.

Colour assessment and browning index

The surface colour of fresh-cut Chinese yam slices was measured using a colorimeter of CM-3700 (Konica Minolta, Inc. Japan) following the method of Fan *et al.* (2019). Three samples were recorded for L^*, a^*, and b^*, and the values were recorded at four positions from four points, of 10 Chinese yam slices, for each treatment group.

The browning index was measured following the method of Jiang (2000) with some modification. A 100 g fresh-cut Chinese yam were homogenised in 10 mL of cold distilled water and 40 mL of acetone at 25°C. Then, the homogenate was filtered by four layers of cotton gauze. The filtrate was further filtered through a vacuum filter. The residue from gauze and vacuum filter was collected and dried with vacuum freeze drying for 20 h to obtain the Chinese yam powder. Next, 2.5 g of Chinese yam powder was added with 50 mL of distilled water, and stirred for 15 min. After centrifuged at 10,000 *g* for 20 min at 4°C, the supernatant was collected. The absorbance was measured at 410 nm by spectrophotometer, and the browning index was expressed as A_{410} nm.

Determination of the total phenolic contents and quinones

The TPC was determined following the procedure of Vanden Abeele *et al.* (2019) with slight modification. Briefly, 3 g of Chinese yam slices was added with 10 mL of 80% methanol, and homogenised for 20 min. Then, the collected filtrate was centrifuged at 13,000 *g* for 30 min at 4°C. Next, 1 mL of

supernatant, 1.58 mL of water, 1 mL of Folin-Ciocalteau (1 mol L^{-1}) reagent, and 3 mL of Na_2CO_3 (200 g L^{-1}) were mixed and centrifugated. Reaction was observed at 25°C after 2 h, following which the absorption value of the mixture at 760 nm was recorded. The content of total phenolics was quantified by the standard curve of gallic acid equivalent (GAE) and expressed as g GAE kg^{-1}.

Determination of quinones was performed following the method of Zhan *et al.* (2013) with slight modification. First, Chinese yam slices (10 g) of different treatment were immersed in 20 mL of methanol for 30 min at 25°C. The crude extract was centrifuged at 4°C for 15 min at 10,000 *g*. Then, the supernatant was used to determine the quinone content, and its concentration was expressed by absorbance value detected at 437 nm.

Assessment PAL, PPO, and POD activities

PAL activity was measured following the method of Li *et al.* (2019b) with slight modification. Chinese yam slices (3 g) were homogenised with 5 mL of 0.1 mol/L precooled borate buffer (pH 8.8). The borate buffer consisted of 6 g polyvinylpyrrolidone (PVPP), 1 mL of Trition X-100, 2 mmol/L ethylenediamine tetra acetic acid (EDTA), and 5 mmol/L β-mercaptoethanol. After 30 min centrifugation at 12,000 *g* and 4°Cw, the obtained supernatant (5 mL) was mixed with $_L$-phenylalanine (20 mmol L^{-1}, 1 mL) and borate buffer (pH 8.0). The variation of absorbance value at 290 nm was taken during 60 min of reaction at 37°C. One unit of PAL activity equalled to the amount of PAL enzyme that caused a change of 0.01 of absorbance at 290 nm, which was expressed as OD_{290} per kg FW per min.

PPO activity was determined following the method of Fan *et al.* (2019) with slight modification. Chinese yam slices (500 g) were randomly selected and blended with 5 mL of precooled acetate buffer (0.1 mol L^{-1}, pH 5.5). After centrifugation at 13,000 g and 4°C for 25 min, 0.5 mL of the supernatant as a PPO enzyme were incubated with 3 mL of 0.01 mol L^{-1} catechol and 2 mL of 0.05 mol L^{-1} acetate-sodium acetate buffer solution (pH 5.5). Finally, the variation of absorbance value at 420 nm were recorded, and the activity of PPO was expressed as OD_{420} per kg FW per min.

POD activity was determined following the method of Liu *et al.* (2019a) with slight modification. Homogenisation was done for 4 g of Chinese yam slices and 5 mL of precooled sodium acetate buffer (0.05 mol L^{-1}, pH 7.6) that consisted of 1 g/100 g PVPP. The homogeneous liquid was centrifuged at 13,000 *g* for 25 min and 4°C. The final 3.7 mL mixture was obtained by adding 0.5 mL of supernatant, 1.9 mL of sodium phosphate buffer (0.05 mol L^{-1}, pH 5.5), 0.8 mL of hydrogen peroxide (10 mmol L^{-1}), and 0.5 mL of guaiacols (0.025 mol L^{-1}), respectively. Finally, the variation of absorbance value at 470 nm were recorded, and the activity of POD was expressed as OD_{470} per kg FW per min.

Real-time quantitative reverse transcription PCR

About 50 g fresh-cut Chinese yam slices were shredded in liquid nitrogen, and about 0.2 g were taken for experiment. Total RNA extraction and purification were done using RNAiso Plus (TaKaRa Biotechnology Co., Ltd.). About 100 ng RNA was used for reverse-transcribed and synthesis to cDNA using Eraser (TaKaRa Biotechnology Co., Ltd.). Gene-specific primers were designed through *Dioscorea* PAL genes in GenBank (PAL, AB016715.1). Ubiquitin was used as an internal control. The sequences of forward and reverse primer were presented as: PAL, CACCTCATCCCACAGA/AACTCCTCCACCATTT; and actin (Ubi), TTGAGACGGCAAAGACCAG/AGGGAAGCCAAGATAGAGC. Real-time quantitative PCR was determined by GoTaq qPCR Analytikjena (Bio-Rad, Hercules, CA). The qPCR reaction parameters were as follows: 95°C for 4 min followed by 40 cycles of 95°C for 25 s, 55°C for 10 s, and annealing at 60°C for 1 min, prolonging for 120 s at 72°C, and collecting fluorescence data for 1 s. In order to target gene research, the PCR reactions were carried out in triplicate.

The headspace atmospheric analysis of O_2 and CO_2

The package headspace gas composition in the packaging was continuously determined with a hand-held O_2/CO_2 breathometer (Shanghai Zhonglin). The probe needle of breathometer was inserted into the packaging bag to determine the gas composition.

Membrane permeability

The electrical conductivity measurement was done as an indicator of the membrane permeability and damage degree in fresh-cut Chinese yam slices according to Liu *et al.* (2019b). Firstly, fresh-cut Chinese yam slices were washed by osmosis (RO) water and punched (10 mm) into uniform discs. Then, the slices were dried by filter paper, mixed into 20 mL of deionised water, and incubated for 30 min as fresh electrolytes. Next, the mixture was boiled for 15 min, and rapidly cooled to 25°C as total electrolytes, which were measured by conductivity meter (Model 3173, Shanghai Electron). The ratio of the fresh sample to

total electrolytes after boiling as the electrical conductivity was then recorded.

Hardness

The hardness of the fresh-cut Chinese yam slices was evaluated using a texture analyser (TA-XT Plus, Stable Systems Ltd., UK) equipped with a cylindroid P2 probe. The Chinese yam samples were fixed on the model platform to prevent the samples from slipping. The pre-test, test, and post-test compression rates of the Chinese yam tissue were 10, 2, and 10 mm/s, respectively. The trigger force strain was 5 g, and the temperature was 25°C. The hardness was determined as the maximum force needed to puncture the fresh-cut yam sample to a depth of 0.5 mm. The results were expressed in N. For each sample, three measurements were performed at each storage time.

Statistical analysis

Experiments were performed in triplicate for each treatment under a completely randomised design. All data were measured for statistical significance using SPSS 13.0, and analysed as means ± standard deviation (SD) with $p \leq 0.05$ accepted as significant by the LSD test.

Results and discussion

UV-C radiation treatment inhibited TBC in fresh-cut Chinese yam

Microbiological evaluation of food was a primary factor in the present work because the inactivation of human pathogens in fresh-cut foods is important in maintaining safety (Yan *et al.,* 2015). UV-C irradiation could decrease the number of total bacterial count in fresh-cut fruits and vegetables during storage (Hosseini *et al.,* 2019). The total number of colonies in all treatments increased with the prolongation of storage time during the 16 days of storage at 4°C. Meanwhile the bacterial count decreased gradually with the increase of irradiation intensity of fresh-cut Chinese yam at 4°C. This is in agreement with a study by Li *et al.* (2019). Inhibition is due to the changing of DNA helix of microorganisms by producing pyrimidine dimer, thus preventing DNA replication (Satoshi *et al.,* 2004). The TBC in the control group increased from log 2.51 CFU/g to log 5.34 CFU/g during the 16-day storage, and the TBC of fresh-cut Chinese yam irradiated with 24 kJ m^{-2} UV-C was completely inhibited as compared to the other treatment.

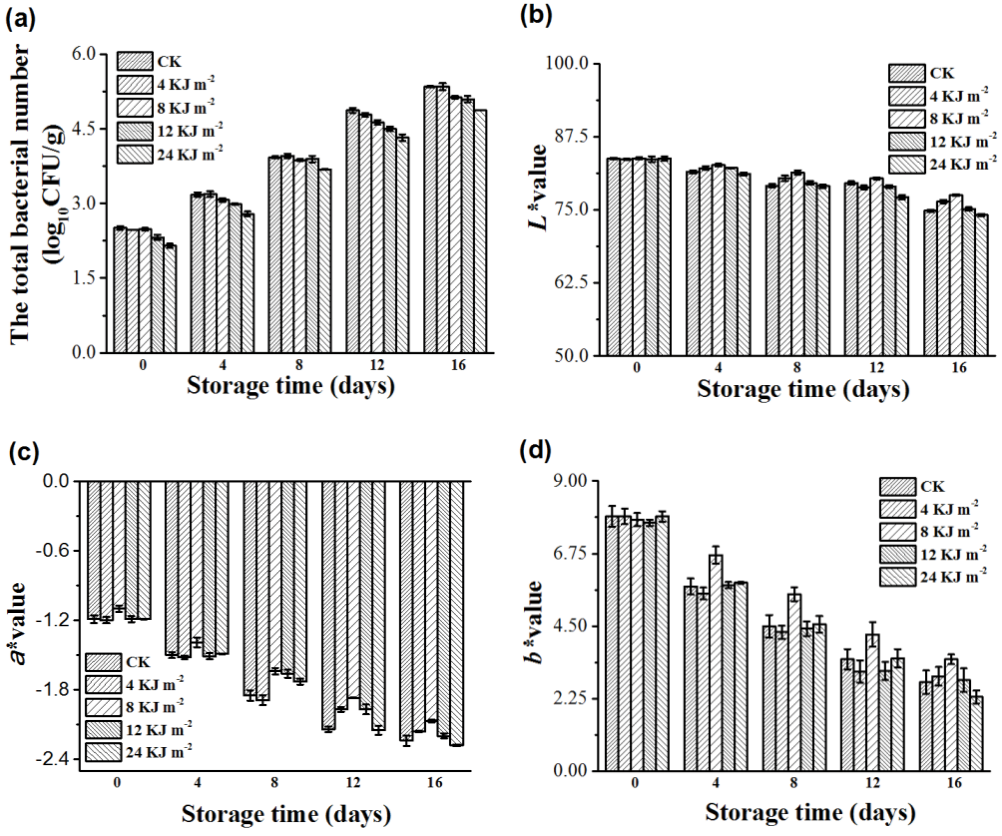

Figure 1. Effect of UV-C radiation intensity on total bacterial number (a), chromaticity L^* (b), a^* (c), and b^* (d) of fresh-cut Chinese yam during storage. Vertical bars represent the standard deviation of the means of triplicate determinations (n = 3).

UV-C radiation treatment inhibited enzymatic browning and colour property

The colour of fresh-cut vegetables directly determines the acceptance of consumers (Ufuk Kasım and Kasım, 2017). Among these treatments, the fresh-cut Chinese yam treated with 8 KJ m^{-2} maintained the colour during storage, while browning of the control group was obvious as evidenced by its lower L^*, a^*, and b^* values (Figure 1).

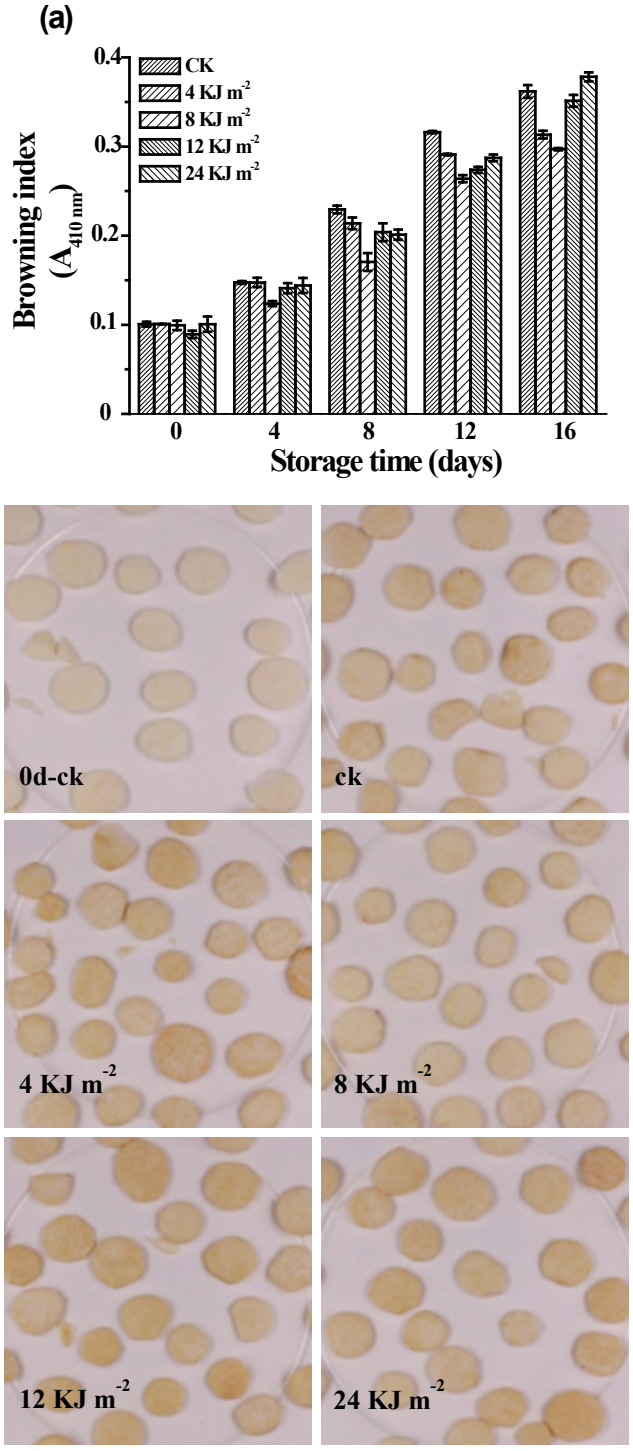

Figure 2. Effect of UV-C radiation intensity on the BI (a) and visual observation (b) of fresh-cut Chinese yam stored for 16 d at 4°C

Browning is an important factor in some fresh-cut vegetables and fruits (Huang *et al.,* 2017). As enzymatic browning progresses, more soluble quinones are produced in fresh-cut vegetables (Sun *et al.,* 2015). Browning index (BI) (Figure 2a), visible quality deterioration (Figure 2b), and soluble quinones (Figure 3) of fresh-cut Chinese yams with different treatments steadily increased during storage at 4°C for 16 days. At day 0, there was no different in BI among all treatments. With the extent of storage time, different treatments indicated different effects on the samples. Radiation intensity (8 kJ m^{-2}) alleviated the increase of BI and soluble quinone contents which were lower at 18% and 4.3% at 16 days, respectively. The total phenolic content gradually increased with the increase of irradiation intensity at 16 days (Figures 3a and 3b). This may be due to the stress response of fresh-cut Chinese yam under external stimulation caused by injury stress (UV-C); the greater the irradiation intensity, the stronger the stress response (Chumyam *et al.,* 2019). These injury stresses promoted the formation of total phenolic content. UV-C radiation at 8 kJ m^{-2} significantly mitigated the BI of fresh-cut Chinese yam, while the yam slices irradiated at 4 and

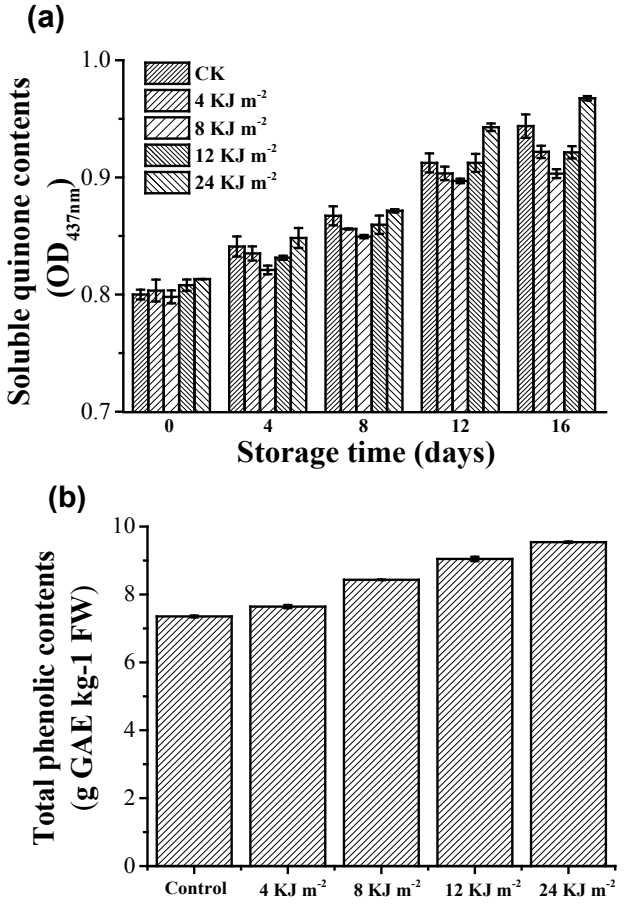

Figure 3. Effect of UV-C radiation intensity on soluble quinone (a) during the storage, and total phenolic (b) at 12 d of fresh-cut Chinese yam.

24 kJ m-2 indicated higher browning degree than those treated with 8 KJ m^{-2}. Interestingly, there was no significant inhibition of browning of fresh-cut Chinese yam with high intensity (24 kJ m^{-2}) treatment. The colour of fresh-cut Chinese yam in the photograph paralleled the BI value. Similarly, according to Wang *et al.* (2019), the browning of fresh-cut lotus root could be best suppressed by the appropriate UV-C irradiation time instead of the longest irradiation time.

Based on our knowledge, browning inhibitor treatment has almost no bacteriostatic effect while inhibiting the browning of fresh-cut vegetables (Chumyam *et al.,* 2019; Zheng *et al.,* 2019). Some physical processing methods could not inhibit the growth of microorganisms while inhibiting browning of fresh-cut vegetable. For example, a short-term carbon dioxide treatment could inhibit the browning of fresh-cut burdock, but had no inhibitory effect on the growth of microorganisms (Dong *et al.,* 2015).

Effect of UV-C treatment on browning-related enzymes activities (POD, PPO, and PAL) and cell damage (electrical conductivity) of fresh-cut Chinese yam

The combination of total phenolic content, enzyme activities, and cell damage are the main cause for browning of fresh-cut Chinese yam (Fan *et al.,* 2017). PPO and POD accelerate the reaction of substrates with oxygen (Richardforget and Gauillard, 1991), and PAL accelerates the formation of browning substrate phenol (Martinez and Whitaker, 1995). Based on the result, the microbial count was unsafe (the total number of microbial was beyond the trade limit of 5 $\log_{10}$ CFU/g). The fresh-cut Chinese yam was irradiated at 4 kJ m^{-2} of UV-C after storage of 16 days, thus the 12th day of shelf life was chosen for further research. The activities of PPO, POD, and PAL were measured on the 12th day of storage.

Different UV-C irradiation intensity had obvious difference in the browning-related enzymatic activities of fresh-cut Chinese yams during storage. PPO activity decreased from 5.12 to 4.26 U•g^{-1}•min^{-1} with the increase in irradiation intensity (Figure 4a). Similarly, the PPO activity of minimally processed *Agaricus bisporus* also decreased under UV-C irradiation (Lei *et al.,* 2018). POD activity of fresh-cut Chinese yams gradually decreased with the increase of irradiation intensity during storage. However, there was no significant difference between the yam with irradiation of 12 and 24 kJ m^{-2} (Figure 4b), which is similar to the minimally processed lily (Hao *et al.,* 2017). PAL activity increased with the increase of irradiation intensity (Figure 4c), and this is similar with PAL activity and total phenolic content of fresh-cut carrots after UV-C irradiation (Formica-Oliveira *et al.,* 2017). The decrease in PPO and POD activities, and increase in PAL activity led to the accumulation of total phenolics (Table 1).

Electrolyte leakage could represent shelf-life quality and membrane damage of fresh-cut Chinese

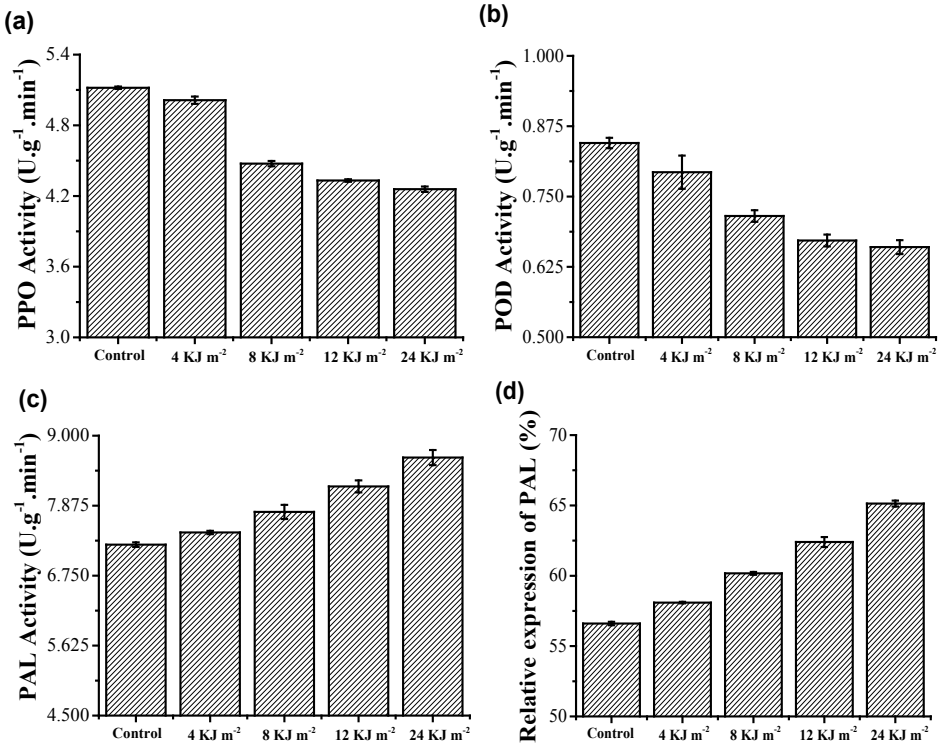

Figure 4. Effect of UV-C radiation intensity on PPO (a), POD (b), PAL (c), and relative expression of PAL (d) at 12 d of fresh-cut Chinese yam.

Table 1. Effect of UV-C treatment on physicochemical properties of fresh-cut Chinese yam.

Parameter	Storage time (days)	UV-C treatment for 0 kJ m^{-2}	UV-C treatment for 8 kJ m^{-2}	UV-C treatment for 24 kJ m^{-2}
Headspace O_2 content (%)	0	18.20 ± 0.04[a]	17.78 ± 0.13[b]	16.88 ± 0.11[c]
	12	7.63 ± 0.12[a]	7.23 ± 0.09[b]	6.98 ± 0.06[c]
Headspace CO_2 content (%)	0	0.78 ± 0.05[a]	0.80 ± 0.04[a]	0.79 ± 0.03[a]
	12	6.38 ± 0.01[c]	6.88 ± 0.12[b]	6.92 ± 0.07[a]
Soluble solid content (%)	0	7.94 ± 0.03[a]	7.91 ± 0.06[a]	7.92 ± 0.05[a]
	12	6.83 ± 0.02[a]	6.81 ± 0.05[a]	6.78 ± 0.07[a]
Hardness (N)	0	5.52 ± 0.03[a]	5.54 ± 0.06[a]	5.57 ± 0.03[a]
	12	3.20 ± 0.14[a]	3.30 ± 0.09[a]	3.42 ± 0.17[a]
Electrical conductivity (%)	0	0.92 ± 0.07[a]	0.97 ± 0.04[a]	0.88 ± 0.06[a]
	12	1.90 ± 0.05[c]	2.10 ± 0.04[b]	2.70 ± 0.07[a]

yam (Delwiche *et al.,* 2019). The conductivity increased with the increase of UV-C intensity (Table 1), which confirmed that UV-C irradiation increased the permeability of fresh-cut Chinese yam cell membrane. Destruction of cell membranes accelerates the binding between enzymes and substrates, which advances the formation of browning (Song *et al.,* 2009).

In summary, the results exhibited that the key factor in controlling the browning of fresh-cut Chinese yam was the enzyme activity (PPO and POD) when the irradiation intensity was lower than 8 kJ m^{-2}, which was due to less damage on the cell. The greater the intensity of UV-C radiation, the more noticeable the inhibition of browning of fresh-cut Chinese yam (irradiation dose: 0 - 8 kJ m^{-2}). However, the damage degree of cell membrane was the key factor that affected browning of fresh-cut Chinese yam when the irradiation intensity was greater than 8 kJ m^{-2}. The high browning degree of yam treated with 12 and 24 kJ m^{-2} UV-C irradiation was due to the increase in contact between enzyme and substrate, thus aggravating the cell damage, increasing cell membrane permeability, and promoting PAL activities, though the POD and PPO activity was suppressed.

UV-C irradiation affected PAL gene expression and activity

PAL activity of fresh-cut Chinese yam was affected by many factors (Jia *et al.,* 2015). Gene expression is one of the important factors affecting PAL enzyme activity. Based on the results (Figure 4d), with the increase in UV-C irradiation intensity, PAL activity and PAL-related expression of yam gradually increased. Similar result has been reported in tomato (Changhong *et al.,* 2018). These results indicated that UV-C irradiation can increase gene expression of PAL in fresh-cut Chinese yam slices. The trend of PAL enzyme activity and total phenolic contents is in agreement with the expression of PAL enzyme gene.

This confirmed that UV-C irradiation stimulated PAL gene expression and consequently promoted PAL activity and synthesis of total phenolics, which increased 7.35 to 9.54 g kg^{-1} FW with the increase in irradiation intensity of UV-C from 4 to 24 kKJ m^{-2}. UV-C irradiation could trigger the defence mechanism of fresh-cut vegetable to promote the formation of total phenolics (Urban *et al.,* 2018).

Effects of UV-C treatment on other physicochemical properties of fresh-cut Chinese yam

The effects of different intensities of UV-C irradiation on the composition of headspace in fresh-cut Chinese yam packaging were significantly different (Table 1). After UV-C irradiation, the concentration of carbon dioxide in the bag significantly increased, while the concentration of oxygen significantly decreased during the 12 days storage of fresh-cut Chinese yam. In conclusion, the UV-C treatment could substantially promote the respiratory rate of fresh-cut Chinese yam during storage.

After 12 days storage, the soluble solid content and hardness of fresh-cut Chinese yam significantly decreased. However, there was no significant difference between UV-C treatment groups and the control during the storage (Table 1), which proved that UV-C treatment had no effect on soluble solids and hardness of the samples.

Conclusion

In conclusion, UV-C irradiation below 8 kJ m^{-2} effectively suppressed the browning of fresh-cut Chinese yam by inhibiting the POD and PPO enzyme activities. The higher the dose, the stronger the inhibition ability. When the irradiation intensity was greater than 8 kJ m^{-2}, PPO and POD enzyme activities

were suppressed, while the destruction of the cell membrane of fresh-cut Chinese yam accelerated the reaction between substrate and enzyme. The role of cell membrane damage was higher than the enzyme activity inactivation which accelerated browning. UV-C irradiation increased the phenol content of fresh-cut Chinese yam by promoting the expression of PAL gene, which correspondingly increased PAL activity and decreased POD and PPO enzyme activities.

Acknowledgments

This work was supported by the Special Training Program for Outstanding Scientists of the Beijing Academy of Agricultural and Forestry Sciences (JKZX201908), the Collaborative Innovation Center of the Beijing Academy of Agricultural and Forestry Sciences (KJCX201915), China Agriculture Research System (CARS-23), and the Efficient Ecological Agriculture Innovation Project of the Taishan Industry Leading Talent Program, Shandong Province (LJNY201705).

References

Bourneow, C. and Toontam, N. 2019. Microbiological quality and some bioactive compounds in relation to sensory profiles during germination of brown-purple-pigmented rice. International Food Research Journal 26(3): 1011-1021.

Changhong, L., Huanhuan, Z., Kangliang, S., Wei, L. and Lei, Z. 2018. Effects of postharvest UV-C irradiation on phenolic acids, flavonoids, and key phenylpropanoid pathway genes in tomato fruit. Scientia Horticulturae 241: 107-114.

Chumyam, A., Faiyue, B. and Saengnil, K. 2019. Reduction of enzymatic browning of fresh-cut guava fruit by exogenous hydrogen peroxide-activated peroxiredoxin/thioredoxin system. Scientia Horticulturae 255: 260-268.

Coelho Júnior, L. F., Ferreira-Silva, S. L., Vieira, M. R., Carnelossi, M. and Simoes, A. N. 2018. Darkening, damage and oxidative protection are stimulated in tissues closer to the yam cut, attenuated or not by the environment. Journal of the Science of Food and Agriculture 99(1): 334-342.

Delwiche, S. R., Stommel, J. R., Kim, M. S., Vinyard, B. T. and Esquerre, C. 2019. Hyperspectral fluorescence imaging for shelf life evaluation of fresh-cut bell and Jalapeno pepper. Scientia Horticulturae 246: 749-758.

Dong, T., Shi, J., Jiang, C. Z., Feng, Y., Cao, Y. and Wang, Q. 2015. A short-term carbon dioxide treatment inhibits the browning of fresh-cut burdock. Postharvest Biology and Technology 110: 96-102.

Fan, K., Zhang, M., Bhandari, B. and Jiang, F. 2019. A combination treatment of ultrasound and ε-polylysine to improve microorganisms and storage quality of fresh-cut lettuce. LWT - Food Science and Technology 113: article ID 108315.

Fan, W., Cao, Y., Ren, H., Wang, Y. and Wang, Q. G. 2017. Effects of ethanol fumigation on inhibiting fresh-cut yam enzymatic browning and microbial growth. Journal of FoodProcessing and Preservation 42(2): article ID e13434.

Formica-Oliveira, A. C., Díaz-López, V., Artés, F. and Artés-Hernández, F. 2017. Effects of UV-B and UV-C combination on phenolic compounds biosynthesis in fresh-cut carrots. Postharvest Biology and Technology 127: 99-104.

Hamon, P. and Toure, B. 1990. Characterization of traditional yam varieties belonging to the *Dioscorea cayenensis-rotundata* complex by their isozymic patterns. Euphytica 46(2): 101-107.

Hao, H., Ge, Z., Limwachiranon, J., Li, L., Li, W. and Luo, Z. 2017. UV-C treatment affects browning and starch metabolism of minimally processed lily bulb. Postharvest Biology and Technology 128: 105-111.

Homaida, M. A., Yan, S. and Yang, H. 2017. Effects of ethanol treatment on inhibiting fresh-cut sugarcane enzymatic browning and microbial growth. LWT - Food Science and Technology 77: 8-14.

Hosseini, F. S., Akhavan, H. R., Maghsoudi, H., Hajimohammadi-Farimani, R. and Balvardi, M. 2019. Effects of a rotational UV-C irradiation system and packaging on the shelf life of fresh pistachio. Journal of the Science of Food and Agriculture 99(11): 5229-5238.

Huang, H., Ge, Z., Limwachiranon, J., Li, L., Li, W. and Luo, Z. 2017. UV-C treatment affects browning and starch metabolism of minimally processed lily bulb. Postharvest Biology and Technology 128: 105-111.

Jamesa, R., Kerryja, I. A., Janneke, T., Craigb, F., Timf, B., Vincentgh, E. and Keithw, W. 2010. Profiling brewers' spent grain for composition and microbial ecology at the site of production. LWT - Food Science and Technology 43(6): 890-896.

Jia, G. L., Shi, J. Y., Song, Z. H. and Li, F. 2015. Prevention of enzymatic browning of Chinese yam (*Dioscorea* spp.) using electrolyzed oxidizing water. Journal of Food Science 80(4):

C718-C728.

Jiang, Y. 2000. Role of anthocyanins, polyphenol oxidase and phenols in lychee pericarp browning. Journal of the Science of Food and Agriculture 80: 305-310.

Kan, J., Xie, W., Wan, B., Huo, T. B., Lin, X. P., Liu, J. and Jin, C. H. 2019. Heat-induced tolerance to browning of fresh-cut lily bulbs (*Lilium lancifolium* Thunb.) under cold storage. Journal of Food Biochemistry 43(5): article ID e12816.

Lei, J., Li, B., Zhang, N., Yan, R., Guan, W., Brennan, C. S., ... and Peng, B. 2018. Effects of UV-C treatment on browning and the expression of polyphenol oxidase (PPO) genes in different tissues of *Agaricus bisporus* during cold storage. Postharvest Biology and Technology 139: 99-105.

Li, M., Li, X., Han, C., Ji, N., Jin, P. and Zheng, Y. 2019a. UV-C treatment maintains quality and enhances antioxidant capacity of fresh-cut strawberries. Postharvest Biology and Technology 156: article ID 110945.

Li, S. T., Lasekan, O., Adzahan, N. M. and Hashim, N. 2016. The effect of combinations of UV-C exposure with ascorbate and calcium chloride dips on the enzymatic activities and total phenolic content of minimally processed yam slices. Postharvest Biology and Technology 120: 138-144.

Li, X., Li, M., Ji, N., Jin, P., Zhang, J., Zheng, Y., ... and Li, F. 2019b. Cold plasma treatment induces phenolic accumulation and enhances antioxidant activity in fresh-cut pitaya (*Hylocereus undatus*) fruit. LWT - Food Science and Technology 115: article ID 108447.

Liu, X., Wang, T., Lu, Y., Yang, Q., Li, Y., Deng, X., ... and Zheng, J. 2019a. Effect of high oxygen pretreatment of whole tuber on anti-browning of fresh-cut potato slices during storage. Food Chemistry 301: article ID 125287.

Liu, X., Yang, Q., Lu, Y., Li, Y., Li, T., Zhou, B. and Qiao, L. 2019b. Effect of purslane (*Portulaca oleracea* L.) extract on anti-browning of fresh-cut potato slices during storage. Food Chemistry 283: 445-453.

Luo, Z., Wang, Y., Jiang, L. and Xu, X. 2015. Effect of nano-CaCO3-LDPE packaging on quality and browning of fresh-cut yam. LWT - Food Science and Technology 60: 1155-1161.

Ma, C., Wang, W., Chen, Y.-Y., Liu, R.-N., Wang, R.-F. and Du, L. 2005. Neuroprotective and antioxidant activity of compounds from the aerial parts of *Dioscorea opposita*. Journal of Natural Products 68: 1259-1261.

Martinez, M. V. and Whitaker, J. R. 1995. The biochemistry and control of enzymatic browning. Trends in Food Science and Technology 6(6): 195-200.

Raseetha, S. and Nadirah, S. 2018. Effect of different packaging materials on quality of fresh-cut broccoli and cauliflower at chilled temperature. International Food Research Journal 25(4): 1559-1565.

Richardforget, F. C. and Gauillard, F. A. 1991. Oxidation of chlorogenic acid, catechins, and 4-methylcatechol in model solutions by combinations of pear (*Pyrus communis* Cv. Williams) polyphenol oxidase and peroxidase: a possible involvement of peroxidase in enzymatic browning. Journal of Agriculture of Food Chemistry 45(7): 2472-2476.

Satoshi, N., Li, L., Shin-Ichiro, K., Masashi, T., Kazuo, Y., Eker, A. P. M. and Akira, Y. 2004. UV light-induced DNA damage and tolerance for the survival of nucleotide excision repair-deficient human cells. Journal of Biological Chemistry 279(45): 46674-46677.

Song, L., Gao, H., Chen, H., Mao, J., Zhou, Y., Chen, W. and Jiang, Y. 2009. Effects of short-term anoxic treatment on antioxidant ability and membrane integrity of postharvest kiwifruit during storage. Food Chemistry 114(4): 1216-1221.

Song, X., Hu, H. and Zhang, B. 2016. Drying characteristics of Chinese yam (*Dioscorea opposita* Thunb.) by far-infrared radiation and heat pump. Journal of the Saudi Society of Agricultural Sciences 17(3): 290-296.

Sun, Y., Zhang, W., Zeng, T., Nie, Q., Zhang, F. and Zhu, L. 2015. Hydrogen sulfide inhibits enzymatic browning of fresh-cut lotus root slices by regulating phenolic metabolism. Food Chemistry 177: 376-381.

Tadeo, P. R. M., Castillo-Israel, K. A. T., Serrano, E. P., Gandia, J. B. L. and Absulio, W. L. 2018. Physiological responses and storage quality of fresh-cut red and white dragon fruit (*Hylocereus* spp.) treated with 1-methylcyclopropene (1-MCP). International Food Research Journal 25(5): 2090-2098.

Tao, R., Zhang, F., Tang, Q.-J., Xu, C.-S., Ni, Z.-J. and Meng, X.-H. 2019. Effects of curcumin-based photodynamic treatment on the storage quality of fresh-cut apples. Food Chemistry 274: 415-421.

Teoh, L. S., Lasekan, O., Adzahan, N. M. and Hashim, N. 2016. The effect of combinations of UV-C exposure with ascorbate and calcium

chloride dips on the enzymatic activities and total phenolic content of minimally processed yam slices. Postharvest Biology and Technology 120: 138-144.

Ufuk Kasım, M. and Kasım, R. 2017. Yellowing of fresh-cut spinach (*Spinacia oleracea* L.) leaves delayed by UV-B applications. Information Processing in Agriculture 4(3): 214-219.

Urban, L., Chabane Sari, D., Orsal, B., Lopes, M., Miranda, R. and Aarrouf, J. 2018. UV-C light and pulsed light as alternatives to chemical andbiological elicitors for stimulating plant natural defenses against fungal diseases. Scientia Horticulturae 235: 452-459.

Vanden Abeele, C., Raes, K. and Sampers, I. 2019. Effect of mild heat treatment on browning-related parameters in fresh-cut Iceberg lettuce. Journal of Food Biochemistry 43: article ID e12906.

Wang, D., Chen, L., Ma, Y., Zhang, M., Zhao, Y. and Zhao, X. 2019. Effect of UV-C treatment on the quality of fresh-cut lotus (*Nelumbo nucifera* Gaertn.) root. Food Chemistry 278: 659-664.

Yan, S., Yang, T. and Luo, Y. 2015. The mechanism of ethanol treatment on inhibiting lettuce enzymatic browning and microbial growth. LWT - Food Science and Technology 63(1): 383-390.

Zhan, L., Hu, J., Lim, L.-T., Pang, L., Li, Y. and Shao, J. 2013. Light exposure inhibiting tissue browning and improving antioxidant capacity of fresh-cut celery (*Apium graveolens* var. dulce). Food Chemistry 141(3): 2473-2478.

Zhang, G., Gu, L., Lu, Z., Yuan, C. and Sun, Y. 2019. Browning control of fresh-cut Chinese yam by edible coatings enriched with an inclusion complex containing star anise essential oil. RSC Advances 9(9): 5002-5008.

Zhang, W. and Jiang, W. 2019. UV treatment improved the quality of postharvest fruits and vegetables by inducing resistance. Trends in Food Science and Technology 92: 71-80.

Zheng, H., Liu, W., Liu, S., Liu, C. and Zheng, L. 2019. Effects of melatonin treatment on the enzymatic browning and nutritional quality of fresh-cut pear fruit. Food Chemistry 299: article ID 125116.