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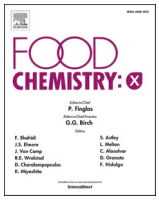

Combination of calcium lactate impregnation with UV-C irradiation maintains quality and improves antioxidant capacity of fresh-cut kiwifruit slices

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ABSTRACT

This study investigated the combined effects of calcium lactate (CA-L, 3 g L^{-1}) and shortwave ultraviolet (UV-C, 4.0 kJ m^{-2}) irradiation on quality attributes and antioxidant defense capacity of fresh-cut kiwifruits at refrigerated storage for 7 d. The results indicated that CA-L and UV-C joint treatment, compared to either treatment alone, alleviated microbial load, showed higher quality on ascorbic acid (AsA), green color, total chlorophyll, flesh hardness, total sugar, total acid and malonaldehyde (MDA) content. Besides, it inhibited $O_2^{\cdot-}$ and $^{\bullet}OH$ generation, induced H_2O_2 production, improved the activity of antioxidant enzymes (SOD, CAT and APX), activated critical enzymes (PAL, C4H and 4CL) in phenylpropanoid metabolism pathway and further enhanced total phenolic and proanthocyanidin content. Above results demonstrated that UV-C together with CA-L treatment could synergistically maintain overall quality and improve antioxidant capacity of kiwifruit slices. Therefore, the combination of CA-L and UV-C treatment showed a potential practical application in fresh-cut kiwifruits.

1. Introduction

Fresh-cut or minimally processed fruits and vegetables are more and more popular among consumers due to their convenience, nutrient-rich and fresh characteristics (Ma, Zhang, Bhandari, & Gao, 2017). In particular, fresh-cut kiwifruits are one of the most attractive commodities in school and company cafeterias, large supermarkets, food service establishments as well as family recipes (Li et al., 2021; Li, Zhang, Liu, Wang, Zhao, & Zong, 2017). Kiwifruit is rich in bioactive phytochemicals, such as ascorbic acid (AsA), polyphenols, dietary fibers, minerals, and organic acids, among others, and it has been reported that regular intake of kiwifruit can promote gut health (Wang, Qiu, & Zhu, 2021). However, fresh-cut fruits and vegetables are generally more perishable than the original intact ones (Benítez, Achaerandio, Pujolà, & Sepulcre, 2015) due to the disruption of the integrity of raw materials caused by mechanical processes such as washing, peeling and cutting, leading to the deteriorative processes including changes in color (enzymatic browning and chlorophyll degradation), tissue softening, off-flavor, water loss, microbial infection and physiological and metabolic disturbance in plant tissues (Teoh, Lasekan, Adzahan, & Hashim, 2016; Xu et al., 2021). Additionally, juice leakage on the surface of fresh-cut fruits and vegetables facilitates microbial growth, which may bring further food safety hazards (Benítez et al., 2015). Numerous postharvest approaches such as heat shock (Chiabrando, Peano, & Giacalone, 2018), cold plasma (Ramazzina et al., 2015), ultraviolet light (Beirao-da-Costa, Conceicao Moura-Guedes, Manuela Ferreira-Pinto, Empis, & Moldao-Martins, 2012), hydrogen sulfide (Gao et al., 2013), edible coating (Passafiume, Gaglio, Sortino, & Farina, 2020), atmospheric modification (Mastromatteo, Mastromatteo, Conte, & Del Nobile, 2011) and association treatments (Beirao-da-Costa et al., 2012; Mastromatteo et al.,

Abbreviations: Shortwave ultraviolet, UV-C; Calcium lactate, CA-L; Ascorbic acid, AsA; Malonaldehyde, MDA; Ferric reducing ability of plasma, FRAP; Phenylalanine ammonium lyase, PAL; Cinnamate-4-hydroxylase, C4H; 4-coumarate coenzyme A ligase, 4CL; Superoxide dismutase, SOD; Catalase, CAT; Ascorbate peroxidase, APX; Reactive oxygen species, ROS.

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2011) are efficient to improve the quality and shelf-life of fresh-cut kiwifruit slices, exploring more effective preservation ways for minimally processed kiwifruits still attracts people's attention.

Shortwave ultraviolet (UV-C, 200–280 nm) irradiation, as a non-thermal sterilization technique, is recognized as a safe and effective treatment for food products by the Food and Drug Administration of USA. It is environmentally friendly, toxic residue-free, easy to operate and inexpensive in equipment (Han, Zhen, Chen, & Fu, 2021; Li, Li, Han, Ji, Jin, & Zheng, 2019; Teoh et al., 2016), and this method has been studied extensively in various fresh-cut products to inactivate the microbial growth, restrain the undesirable flavors, inhibit browning process, reduce softening, delay the ripening, prolong the shelf-life and preserve the optimal quality during storage (Gonzalez-Aguilar, Villegas-Ochoa, Martinez-Tellez, Gardea, & Ayala-Zavala, 2007; Han et al., 2021; Li et al., 2021; Li et al., 2019; Wang, Chen, Ma, Zhang, Zhao, & Zhao, 2019). Additionally, low dose irradiation of UV-C can be an abiotic stress hormesis to intervene the primary or secondary metabolism (Duarte-Sierra, Tiznado-Hernandez, Jha, Janmeja, & Arul, 2020; Han et al., 2021; Li et al., 2019), activating the antioxidant enzymes defense system, and upregulating the biosynthesis of health-promoting phytochemicals including polyphenols, terpenes, γ-aminobutyric acid and other bioactive phytochemicals, at the injured or adjacent site to defend and heal the mechanical damages (Cisneros-Zevallos, 2003). These bioactive substances exhibit antioxidant capacity, antitumor, antimicrobial and gut health-promoting effects (Li et al., 2019; Wang et al., 2021). The combination of UV-C with other preservative treatments is of practical value to boost the effectiveness of UV-C. Several studies in the literature have demonstrated the synergistic effect of UV-C when combined with ascorbate and calcium chloride impregnations (Teoh et al., 2016), high-oxygen modified atmosphere packaging (Li et al., 2021) and heat treatment (George, Razali, Santhirasegaram, & Somasundram, 2015).

Calcium salts have been widely employed to maintain the quality of many delicate fresh fruits and vegetables, such as calcium lactate (CA-L), calcium chloride, calcium phosphate, calcium propionate and calcium gluconate (Naser, Rabiei, Razavi, & Khademi, 2018). Among various calcium salts, calcium chloride is one of the most commonly used ones to delay softening, decrease physiological disorders and extend the post-harvest storage life of fresh agricultural products (Prajapati, Asrey, Varghese, & Sharma, 2021). But several undesirable defects significantly drag down its application, for example, calcium chloride imparted an undesirable bitter taste in fresh-cut cantaloupes (Luna-Guzmán & Barrett, 2000), remained unacceptable salty taste in blackberries (Hanson, Beggs, & Beaudry, 1993) and even produced carcinogens compounds (chloramines and trihalomethanes) attributed to the residual chlorine of inorganic calcium salts (Martin-Diana, Rico, Frias, Barat, Henehan, & Barry-Ryan, 2007). Organic calcium salts, especially CA-L, can be an ideal alternative source of calcium because it can maintain better textural attributes and avoid the weaknesses of calcium chloride (Abd-Elhady, 2014; Alandes, Pérez-Munuera, Llorca, Quiles, & Hernando, 2009; Naser et al., 2018; Prajapati et al., 2021). CA-L is used as a food additive and is permitted to be used in fresh sliced fruits and vegetables in China GB 2760–2014 (2014). Many investigations have reported that CA-L is quite useful not only to prevent the softening and suppress the growth of microbe on fresh-cut cantaloupes (Luna-Guzmán & Barrett, 2000), fresh-cut pears (Alandes et al., 2009) and fresh-cut papayas (Mirshekari & Madani, 2021), but also to increase the calcium content which may represent an interesting way to enhance the essential macronutrient elements of fresh foods (Abd-Elhady, 2014). Furthermore, Previous reports have shown that CA-L plays a positive role in accumulation of total phenols and antioxidant capacity during storage of fresh products (Barzegar, Fateh, & Razavi, 2018; Mirshekari & Madani, 2021; Naser et al., 2018; Prajapati et al., 2021).

To the best of our knowledge, although either calcium dipping (Beirao-da-Costa, Empis, & Moldao-Martins, 2014) or UV-C irradiation (Beirao-da-Costa et al., 2012) has been reported to maintain quality of fresh-cut kiwifruits, the information of the combination of CA-L impregnation and UV-C irradiation on fresh-cut kiwifruits is rarely reported in the literature. Therefore, the main objective of this paper was to investigate the potential effect of CA-L combined with UV-C treatments on microbial load, quality attributes and vitro antioxidant capacity of fresh-cut kiwifruits during refrigerated storage at 4 ± 1 ℃ for 7 d. In addition, the changes of antioxidant capacity were evaluated through critical parameters related to the phenolic compounds metabolism and antioxidant enzymes defense system.

2. Materials and methods

2.1. Fruit materials and fresh-cut processing

Fresh kiwifruit (*Actinidia deliciosa* cv. Hayward) at commercial maturity was obtained from an orchard in Zhouzhi county, Shaanxi province of China in the beginning of November 2020.

After harvest, fruits were immediately transported to the laboratory, and intact fruits with uniform shape and size were selected as experimental raw materials and stored at 4 ± 1 ℃ for post-ripening until the commercial maturity kiwifruit turned into edible maturity (the content of soluble solids was greater than 10 °Brix) before it was used for fresh-cut processing. In this study, a portable sugar meter was regularly employed to quickly determine the soluble solids content. The experiment was carried out when the kiwifruit soluble solid content was monitored at 10.8 ± 0.1 °Brix. Meanwhile, other basic indicators of the samples were detected (single fruit weight of 134.76 ± 5.73 g, hardness of 2.85 ± 0.08 N, and titratable acidity of 9.57 ± 0.05 g of malic acid kg^{-1} on a fresh weight basis) under this soluble solid level. After selection, the fur and stains on the surface was scrubbed with tap water, fruits were then sanitized with 200 μL L^{-1} of sodium hypochlorite for 2 min, rinsed with running water and naturally drained for half an hour. After that, kiwifruit slices with 1 cm thickness were obtained by a sterilized sharp stainless-steel knife. The slices were immediately dipped in distilled water for 1 min to eliminate the cellular fluid (Teoh et al., 2016).

UV-C equipment was assembled similar to Teoh et al. (2016), Li et al. (2019) and Li et al. (2021) with slight differences. Six UV-C lamps (Model TUV 8 W G6 T5, Philips Luminaires Co. Ltd., Shanghai, China) with maximal emission at 254 nm were evenly installed on the top and bottom of chamber with interval distance of 15 cm from each other. A stainless-steel (grade 304 for food usage) mesh tray was fixed in the middle of the chamber with a distance of 30 cm to upper or lower UV-C lamps. The intensity of UV-C light was measured by UV-C light meter (Model ST512, Sentry Optronics Corp., Taiwan, China). Under this device, the sample was exposed for 1 min equivalent to UV-C dose of 0.8 kJ m^{-2}, which was calculated as the mean of 42 UV-C intensity readings measured within a uniform area of the radiation field.

The kiwifruit slices were randomly divided into 4 groups for different treatments: (1) Control, the slices were only dipped in distilled water for 5 min; (2) CA-L, kiwifruit slices were immersed in 3 g L^{-1} CA-L for 5 min; (3) UV-C, kiwifruit slices were irradiated by UV-C with 4.0 kJ m^{-2}; (4) CA-L + UV-C, slices were treated with 3 g L^{-1} CA-L first and then irradiated by 4.0 kJ m^{-2} UV-C. The selected CA-L concentration and UV-C dose were based on preliminary experiments. After treatments, samples were packed with 16 × 16 × 2 cm polyethylene terephthalate (PET) trays covered with polyvinyl chloride (PVC) films and stored at 4 ± 1 ℃ with 90 ± 5% relative humidity for 7 d. During storage, the evaluations of samples were taken every two days with three repetitions of each treatment. Some of the fresh samples were used for immediate determination, while others were flash frozen with liquid nitrogen and stored in ultra-low temperature refrigerator at −80 ℃ until use.

2.2. Microbiological determinations

Aerobic plate count and enumeration of moulds and yeasts of fresh-

cut kiwifruits were determined based on the procedure of Li et al. (2017). Briefly, 25 g kiwifruit were homogenized with 225 mL sterile saline (0.85%) in an aseptically homogeneous bag by germfree homogenizer (Model 10–315, Scientz Bio-tech Co., Ltd. Ningbo, China) at a normal speed for 3 min. Serial decimal dilutions were then obtained and appropriate decimal dilution were spread on Plate Count Agar (Aoboxing Bio-tech Co., Ltd. Beijing, China) for 48 ± 2 h at 36 ± 1 ℃ for aerobic plate count, and Rose Bengal Medium (Aoboxing Bio-tech Co., Ltd. Beijing, China) for 5 d at 28 ± 1 ℃ for moulds and yeasts count. The results were expressed as $\log_{10}$ CFU g^{-1} based on fresh weight.

2.3. Quality attributes assessments

2.3.1. Determinations of flesh color and total chlorophyll content

The color of kiwifruit slices was determined by a precision Colorimeter (Model SC-10, 3nh Technology Co. Ltd., Shenzhen, China), according to the procedure described by Passafiume et al. (2020) with slight modifications. There were 18 slices (6 slices as a replicate) for each group at each sampling time and 6 different locations on the circumference of each slice were measured.

Total chlorophyll content was determined referring to the procedure described by Li et al. (2017) with minor modifications. Briefly, 5 g sample was ground with 15 mL iced acetone and 0.5 g calcium carbonate. After extracting for 30 min at 4 ℃, the mixture was centrifuged at 10,000 × *g* for 10 min at 4 ℃. The supernatant was directly used to determine the total chlorophyll content by an Elisa Reader (Model Varioskan Flash, Thermo Fisher Scientific Inc., Waltham, MA, USA) at 663 nm and 664 nm. The results were calculated as described by Arnon (1949) and expressed as mg kg^{-1} based on fresh weight.

2.3.2. Determinations of flesh hardness and malonaldehyde (MDA) content

The hardness of fresh-cut kiwifruits was determined using a texture analyzer (Model TA. XTPlus, Stable Micro Systems Ltd., Surrey, UK) with a P/5 probe, as described by Chiabrando et al. (2018). Texture profile analysis (TPA) mode was used for the determination of 18 kiwifruit slices (6 slices as a replicate) in each group at each sampling time, and 6 points at equal interval along the edge of each slice were determined. Pre-test, test and post-test speed was 5, 1 and 10 mm s^{-1}, respectively. Trigger force was 5 g and penetrating distance was 4 mm.

MDA content was determined based on the method by Shen, Zhang, Devahastin, and Guo (2019). Briefly, 100 g L^{-1} trichloroacetic acid (TCA) (15 mL) was used to extract the MDA in 2 g samples. The mixture was then centrifuged at 10,000 × *g* for 20 min at 4 ℃. 2 mL supernatant and 2 mL 6.7 g L^{-1} thiobarbituric acid were mixed and kept in boiled water bath for 20 min, and centrifuged again. Finally, the absorbance values at 450, 534 and 600 nm were recorded. The results were calculated as described by Hodges, DeLong, Forney, and Prange (1999) and expressed as μmol kg^{-1} based on fresh weight.

2.3.3. Determinations of total sugar and total acid content

Total sugar content was determined according to the anthrone-sulfuric acid colorimetry as described by Leyva, Quintana, Sánchez, Rodríguez, Cremata, and Sánchez (2008) with some modifications. Firstly, 1 g frozen tissues were ground with 10 mL distilled water and incubated in boiled water bath for 30 min to extract the sugar and then filtered. The residue was extracted again with distilled water (10 mL) for 10 min, the filtrates were then combined and transferred to a 50 mL volumetric flask. Subsequently, 0.01 mL filtrate was mixed with 0.39 mL distilled water, 0.1 mL anthrone-ethylacetate (20 g L^{-1}) and 1 mL concentrated sulfuric acid (98%), and incubated for 1 min in boiling water. Eventually, the absorbance at 620 nm was determined and the total sugar content was expressed as g kg^{-1} based on fresh weight.

Total acid content in kiwifruit tissues was determined referring to the acid-base titration method as described by Li et al. (2017). Briefly, 10 g frozen samples were homogenized with 20 mL distilled water and incubated in boiled water for half an hour. The mixture was filtered and the filtrate was made up to 100 mL for determination. 0.05 mol L^{-1} sodium hydroxide was used to titrate the filtrate (20 mL) containing 2 drops of phenolphthalein (10 g L^{-1}). The total acid content was expressed as g kg^{-1} of malic acid based on fresh weight.

2.4. Antioxidant capacity assessments

To determine the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging capacity of fresh-cut kiwifruits, the modified approach by Yang, Shen, Li, Huang, and Cheung (2015) was used. Briefly, 5 g frozen kiwifruits were ground and extracted with 15 mL cold methanol for 12 h at 4 ℃ in dark. The mixture was centrifuged at 12,000 × *g* for 20 min at 4 ℃ and the supernatant was collected. 0.1 mL supernatant was then mixed with 0.8 mL DPPH radical solution (0.2 mmol L^{-1}) and incubated at 25 ℃ for 30 min in dark. The absorbance at 515 nm was monitored. Trolox was used to make standard curves and the DPPH radical scavenging capacity was described as g of trolox equivalent (TE) kg^{-1} on the basis of fresh weight.

The determination of diammonium 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonate) (ABTS) radical scavenging capacity of fresh-cut kiwifruits was based on Yang et al. (2015). Briefly, ABTS radical solution was obtained by mixing equal volumes of 7 mmol L^{-1} ABTS solution and 2.45 mmol L^{-1} potassium persulfate for 16 h at room temperature in dark. Then the stock solution was diluted with methanol to an absorbance of 0.89 at 734 nm as ABTS radical working solution. After that, 0.05 mL supernatant was mixed with 0.8 mL the working solution and 0.05 mL methanol and incubated for 4 min at 30 ℃ in dark. The absorbance was set at 734 nm and the ABTS radical scavenging capacity was described as g TE kg^{-1} on the basis of fresh weight.

The ferric reducing ability of plasma (FRAP) of fresh-cut kiwifruit slices was assayed referring to the approach of Yang et al. (2015) with slight modifications. Briefly, 0.3 mol L^{-1} sodium acetate buffer (pH 3.6), 20 mmol L^{-1} ferric chloride, and 10 mmol L^{-1} 2,4,6-Tris(2-pyridyl)-1,3,5-triazine in 40 mmol L^{-1} HCl solution were mixed in a volume ratio of 10:1:1 as FRAP working reagent. The FRAP working reagent (0.6 mL) was added to the supernatant (0.05 mL) and methanol (0.05 mL) and incubated at 37 ℃ for 4 min in dark, the absorbance of mixture was recorded at 593 nm and the results were described as g TE kg^{-1} on the basis of fresh weight.

The total reducing capacity of fresh-cut kiwifruit slices was assayed according to the approach of Yang et al. (2015) with minor modifications. Briefly, the supernatant (0.02 mL) and methanol (0.08 mL) were mixed with 10 g L^{-1} potassium ferricyanide in 0.2 mol L^{-1} sodium phosphate buffer at pH 6.6 (0.1 mL) and incubated for 20 min at 50 ℃ in dark. Then 100 g L^{-1} TCA (0.1 mL), 1 g L^{-1} ferric chloride (0.06 mL) and deionized water (0.3 mL) were added into the mixture and incubated for 30 min at 50 ℃ in dark. The absorbance was read at 700 nm and the results were described as g TE kg^{-1} on the basis of fresh weight.

2.5. Antioxidant measurements

AsA content in kiwifruit slices was measured using the o-phenanthroline colorimetric method of Han et al. (2021) with slight modifications. 2 g frozen kiwifruit tissues were extracted with 50 g L^{-1} TCA (10 mL) and centrifuged at 10,000 × *g* for 20 min at 4 ℃. 0.4 mL supernatant was mixed with 0.2 mL anhydrous ethanol, 0.1 mL phosphoric acid (0.4%, v/v), 0.2 mL phenanthroline (5 g L^{-1}) and 0.1 mL ferric chloride (3 g L^{-1}), and incubated for an hour at 30 ℃ in dark. The absorbance at 534 nm was recorded and the AsA content was expressed as g kg^{-1} based on fresh weight.

Total phenolic content was measured following the Folin-Ciocalteu method by Wang et al. (2019) with slight variation. The extraction of phenols was consistent with that in antioxidant capacity. 0.2 mL extract was mixed with 1 mL Folin-Ciocalteu reagent (0.1 mol L^{-1}) and incubated for 3 min at 25 ℃ in dark and immediately follows by adding 1 mL sodium carbonate (75 g L^{-1}). After 30 min of reaction at 25 ℃ in dark,

the absorbance of reaction mixture was registered at 765 nm. The total phenolic content was described as g kg^{-1} of gallic acid equivalents (GAE) based on fresh weight.

Proanthocyanidin content in fresh-cut kiwifruits was measured following the vanillin-sulfuric acid colorimetry by Sun, Leandro, Ricardo da Silva, and Spranger (1998) with slight changes. After the extraction, 0.3 mL extract was mixed with 0.75 mL vanillin (50 g L^{-1} in methanol) and 0.75 mL sulfuric acid (20%, v/v in methanol) and incubated for 20 min at 30 ℃ in dark. The absorbance was monitored at 500 nm and the proanthocyanidin content was described as g kg^{-1} of catechin equivalents (CE), which based on fresh weight.

2.6. Analysis of crucial enzymes activities in phenylpropanoid pathway

The modified procedure based on Han et al. (2021) was used to analyze phenylalanine ammonium lyase (PAL) activity in kiwifruit slices. 5 g frozen samples were pestled in 15 mL 0.1 mol L^{-1} sodium borate buffer (pH 8.8, containing 2 mmol L^{-1} ethylenediamine tetraacetic acid (EDTA), 40 g L^{-1} polyvinylpyrrolidone (PVP) and 5 mmol L^{-1} β-mercaptoethanol). Next the mixture was centrifuged at 12,000 × *g* for 30 min at 4 ℃, and 0.5 mL extract was mixed with 0.5 mL L-phenylalanine (20 mmol L^{-1}) and 3 mL sodium borate buffer at pH 8.8 (50 mmol L^{-1}). The blank sample was obtained by keeping the extract at boiled water bath for 10 min. After 1 h incubation at 37 ℃, the reaction was immediately terminated by adding 0.1 mL hydrochloric acid (HCl) (6 mol L^{-1}) and the reading was recorded at 290 nm. The results were expressed as U kg^{-1} based on fresh weight, where one unit of PAL activity was equal to a variation of 0.01 in absorbance per second.

A modification of the procedure described by Li et al. (2019) was used to determine cinnamate-4-hydroxylase (C4H) activity in kiwifruit slices. 5 g frozen samples were ground with 15 mL Tris-HCl buffer (50 mmol L^{-1}, pH 8.9, containing 10 μmol L^{-1} leupeptinand, 1 mmol L^{-1} phenylmethanesulfonyl fluoride, 4 mmol L^{-1} magnesium chloride ($MgCl_2$), 5 mmol L^{-1} AsA, 15 mmol L^{-1} β-mercaptoethanol, 1.5 g L^{-1} PVP and 10% (v/v) glycerol). The mixture was centrifuged at 12, 000 × *g* for 30 min at 4 ℃, and 0.5 mL supernatant was mixed with 2.5 mL Tris-HCl buffer (50 mmol L^{-1}, pH 8.9, containing 2 μmol L^{-1} trans-cinnamic acid, 5 μmol L^{-1} D-glucose-6-phosphate disodium salt and 2 μmol L^{-1} NADP-Na_2). After 30 min incubation at 25 ℃, 0.1 mL HCl (6 mol L^{-1}) was added into the mixture to terminated the reaction and the absorbance at 340 nm was monitored. C4H activity was described as U kg^{-1} of kiwifruit on fresh weight basis, one unit was equal to the enzyme quantity causing a change of 0.01 in absorbance per second.

A modification of the procedure described by Li et al. (2019) was used to determine 4-coumarate coenzyme A ligase (4CL) activity in kiwifruit slices. The extraction was the same as C4H activity. 0.5 mL extracted supernatant was mixed with 2 mL $MgCl_2$ (5 mmol L^{-1}), 0.5 mL adenosine triphosphate (5 mmol L^{-1}), 0.05 mL *p*-cumaric acid (0.6 mmol L^{-1}) and 0.05 mL coenzyme A (0.4 mmol L^{-1}). After 10 min incubation at 40 ℃, the reaction was immediately stopped by adding 0.1 mL HCl (6 mol L^{-1}) and the absorbance at 333 nm was monitored. 4CL activity was described as U kg^{-1} on the basis of fresh weight, one unit was the changes in 0.01 in absorbance per second.

2.7. Analysis of antioxidant enzymes activities

The activity of superoxide dismutase (SOD) was analyzed based on the approach of Xu et al. (2021) with minor modifications. 5 g frozen tissue was ground with 15 mL sodium phosphate buffer (0.1 mol L^{-1}, pH 7.8, containing 5 mmol L^{-1} dithiothreitol and 50 g L^{-1} PVP) and centrifuged at 12, 000 × *g* for 30 min at 4 ℃. 0.1 mL supernatant was mixed with 1.7 mL sodium phosphate buffer (50 mmol L^{-1}, pH 7.8), 0.3 mL L-methionine (130 mmol L^{-1}), 0.3 mL nitrotetrazolium blue chloride (NBT) (750 μmol L^{-1}), 0.3 mL EDTA-Na_2 (100 μmol L^{-1}), and 0.3 mL riboflavin (20 μmol L^{-1}). The reaction was illuminated under 4000 lx lamp for 15 min at room temperature and the absorbance at 560 nm was determined. The one without light exposure was used as blank. One unit of SOD activity was defined as the enzyme amount that caused 50% inhibition of NBT photochemical reduction per second and the results were described as U kg^{-1} based on fresh weight.

The activity of catalase (CAT) was evaluated according to the approach of Xu et al. (2021) with some modifications. The enzyme extraction was the same as SOD activity. After the extraction, 0.2 mL supernatant was blended with 2.8 mL H_2O_2 (hydrogen peroxide, 20 mmol L^{-1}), the absorbance at 240 nm was immediately determined every 30 s for 6 consecutive times. One unit of enzyme activity was the decrease of 0.01 in absorbance per second and U kg^{-1} of kiwifruit on fresh weight basis was used to describe the CAT activity.

The activity of ascorbate peroxidase (APX) was estimated referring to the approach of Xu et al. (2021) with slight modifications. 5 g frozen samples were ground with 15 mL potassium phosphate buffer (0.1 mol L^{-1}, pH 7.5, containing 0.1 mmol L^{-1} EDTA, 1 mmol L^{-1} AsA and 20 g L^{-1} PVP), and then centrifuged at 12,000 × *g* for 30 min at 4 ℃. 0.2 mL supernatant was mixed with 0.3 mL H_2O_2 (2 mmol L^{-1}) and 2.5 mL reaction buffer (pH 7.8, containing 50 mmol L^{-1} potassium phosphate, 0.1 mmol L^{-1} EDTA and 50 mmol L^{-1} AsA). The absorbance at 290 nm of the mixture was immediately determined every 30 s for 6 consecutive times. One unit of enzyme activity was the changes of 0.01 in absorbance per second and U kg^{-1} based on fresh weight was used for describing the APX activity.

2.8. Reactive oxygen species (ROS) measurements

The measure of $O_2^{\cdot-}$ production was carried out by a modification of the method as described by Li et al. (2019). 5 g frozen samples were homogenized with 15 mL sodium phosphate buffer (50 mmol L^{-1}, pH 7.8, containing 1 mmol L^{-1} EDTA, 20 g L^{-1} PVP and 0.3% (v/v) triton X-100). Subsequently, the mixture was centrifuged at 12,000 × *g* for 20 min at 4 ℃ and non-organic phase layer of the supernatant was collected and used for measuring the $O_2^{\cdot-}$ production. 0.25 mL extract was mixed with 0.25 mL hydroxyl ammonium chloride (1 mmol L^{-1}) and incubated for one hour at 25 ℃ in dark. Then 0.5 mL 4-aminobenzenesulfonic acid (17 mmol L^{-1}) and 0.5 mL 1-naphthylamine (17 mmol L^{-1}) were added to the reaction medium and incubated for 20 min. The absorbance at 530 nm was read and the $O_2^{\cdot-}$ production was expressed as nmol s^{-1} kg^{-1} based on fresh weight.

The measure of •OH content was conducted with the modified method described by Fenton (1894). The extract procedure was the same as $O_2^{\cdot-}$. After extraction, 0.5 mL the supernatant was mixed with 0.5 mL methyl violet (0.02 mmol L^{-1}, pH 3.5) and reacted for 10 min at 25 ℃ in dark. The absorbance value at 580 nm was recorded. The blank sample contained only extraction. The •OH content were indirectly expressed as ΔA kg^{-1} based on fresh weight.

The H_2O_2 content was measured with the modified method described by Gay and Gebicki (2000). 5 g frozen tissues were ground with 15 mL cooled acetone and centrifuged at 12, 000 × *g* for 20 min at 4 ℃. The extraction mixture in order to isolate chlorophyll including carbon tetrachloride (3 mL), deionized water (2 mL) and supernatant (1 mL). Then upper aqueous phase layer was collected. 0.5 mL extraction was added into 1 mL working reagent and incubated for 30 min at 30 ℃ in dark. The working reagent was composed of reagent A and B at a volume ratio of 1:10, where reagent A consisted of 3.3 mmol L^{-1} ferrous sulfate, 3.3 mmol L^{-1} ammonia sulfate and 412.5 mmol L^{-1} sulfuric acid, reagent B consisted of 165 μmol L^{-1} xylenol orange and 165 mmol L^{-1} sorbitol. The absorbance at 560 nm was recorded and the H_2O_2 content was expressed as μmol kg^{-1} of kiwifruit on fresh weight basis.

2.9. Statistical analysis

Experiments were arranged in a completely randomized design. Data were represented as the mean values with standard errors of triplicates

and one-way analysis of variance (ANOVA) based on the SAS Version 9.4 (SAS Institute Inc., Cary, NC, USA) was applied. Duncan's multiple range tests were used to compare the mean separations and differences at $p < 0.05$. Correlation analysis of all the parameters was conducted with Correlation Plot (Version 1.30) by OriginPro2021's plugin (Origin Lab Corp., Northampton, MA, USA).

3. Results and discussions

3.1. Effect of CA-L and UV-C combined treatment on aerobic plate count and moulds and yeasts of fresh-cut kiwifruits

As shown in Fig. 1A, aerobic plate count gradually increased during refrigerated storage for one week, and it was significantly lower in UV-C and CA-L + UV-C groups than that in control and CA-L groups at the initial time, which indicated that microbial load in kiwifruit slices was immediately reduced by UV-C irradiation treatment. CA-L, UV-C and CA-L + UV-C showed lower aerobic plate count than control at the end of storage. Moreover, the aerobic plate count in CA-L + UV-C treated group had the lowest levels throughout the whole storage. Likewise, moulds and yeasts in kiwifruit slices exhibited similar trend as that of aerobic plate count (Fig. 1B). Even though there were no significant difference on the initial moulds and yeasts among the groups, indicating that UV-C irradiation treatment did not decrease moulds and yeasts, UV-C and CA-L + UV-C groups showed much lower moulds and yeasts than control and CA-L groups during storage. Besides, no obvious difference between CA-L + UV-C and UV-C groups can be detected, indicating CA-L may not affect the growth of moulds and yeasts. The acceptable microbial limit for fresh-cut kiwifruit slices is below the 6 $\log_{10}$ CFU g^{-1} according to the EU Regulation (No. 2073/2005). CA-L and UV-C alone or in combination showed effective inhibitory effects on microbial growth of aerobic plate count and moulds and yeasts in fresh-cut kiwifruit slices during cold storage for 7 d. And synergistic effect of CA-L and UV-C was observed on aerobic plate count, which was also reported by many other studies that applied UV-C and other preservation methods on fresh-cut products, such as fresh-cut carrots (Li et al., 2021), kiwifruits (Beirao-da-Costa et al., 2012) and strawberries (Li et al., 2019).

3.2. Effect of CA-L and UV-C combined treatment on flesh color, total chlorophyll content, flesh hardness, MDA content, total sugar and acid content of fresh-cut kiwifruits

The color, texture and taste of fresh-cut fruits and vegetables directly affect the purchase intention of consumers. The green color of 'Hayward' kiwifruit slices is attributed to the presence of chlorophyll (Passafiume et al., 2020), and the a* value represents the color from green to red that can reflect the degree of greenness. As illustrated in Fig. 2A, the differences in a* value were increased during the storage, probably due to the degradation of chlorophyll. CA-L + UV-C group showed lower a* value compared with other groups, which signified that this combination was able to maintain the bright green color of kiwifruit slices and delay the decline of chlorophyll. Fig. 2B presented that the total chlorophyll content of fresh-cut kiwifruits gradually decreased throughout storage time. In particular, it was sharply dropped on day 3 in control group and remained relatively stable during the subsequent storage. While for CA-L + UV-C group, chlorophyll only slightly decreased and the total chlorophyll content was noticeably higher than other groups after 5 d of storage. Obtained results suggested that the combination of CA-L and UV-C kept substantially the original greenness of samples by suppressing chlorophyll degradation. Similar results were also reported in previous literatures, for example, UV-C treatment preserved chlorophyll of fresh-cut stem lettuce (Han et al., 2021) and CA-L treatment conserved chlorophyll of bitter gourd fruit (Prajapati et al., 2021).

As can be seen in Fig. 2C, the flesh hardness of fresh-cut kiwifruits displayed an obvious decline along with the storage time. CA-L + UV-C treated group presented markedly higher hardness than other groups on day 3 and remained relatively stable afterwards, which implied that the combined treatment could be conducive to restrain the tissue softening. MDA is the main product of membrane lipid peroxidation caused by the accumulation of ROS (Shen et al., 2019), the higher the MDA content in the samples, the greater the damage of cell membrane. Fig. 2D shows that the MDA content in kiwifruit slices gradually increased along with the storage time. In control group, MDA content was more than that in other groups at the end of the experiment. Moreover, the MDA content in CA-L + UV-C group remained the lowest during the whole storage period, possibly due to the maintenance of cell integrity by CA-L and the antioxidant defense capacity of the cell against ROS. Based on these results, CA-L and UV-C joint treatment was superior to restrain the MDA production, retard the cell membrane peroxidation and further maintain the texture of fresh-cut kiwifruit slices. This finding was accord with other works (Li et al., 2021; Shen et al., 2019; Xu et al., 2021).

The sweet and sour taste of kiwifruit are strongly linked to the sugar and organic acid content. From Fig. 2E, the total sugar content in all the groups elevated during the first day of storage at similar level, which was probably attributed to the fruit ripening caused by abundant ethylene generated by wounded respiration, leading to the conversion of starch into sugar. Subsequently, however, a slowly fall of total sugar

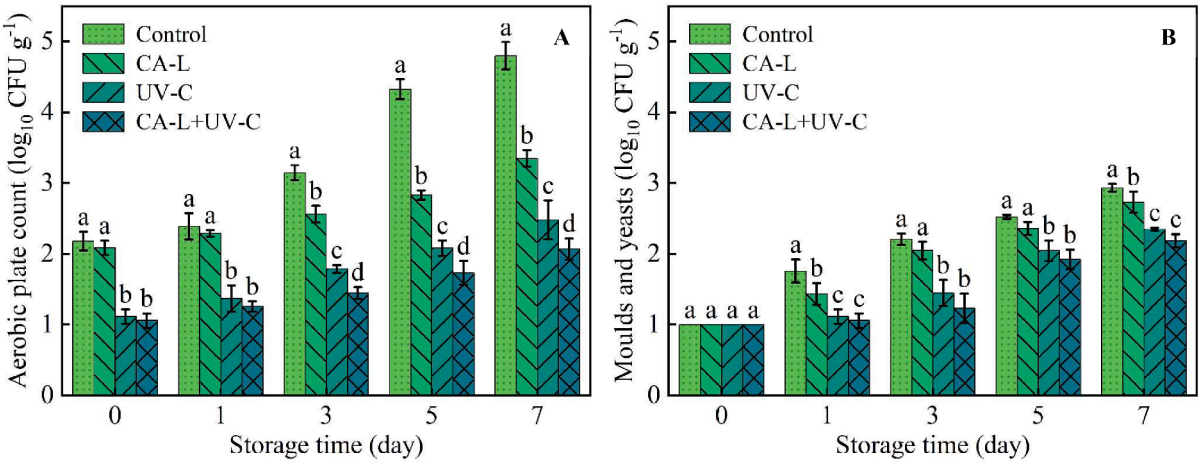

Fig. 1. Effect of CA-L impregnation and UV-C irradiation on aerobic plate count (A) and moulds and yeasts (B) of fresh-cut kiwifruits during one week of storage at 4 ℃. Columns with vertical bars represent the mean ± standard errors of triplicates. Different letters above the vertical bars at the same storage time stand for statistically significant differences at $p < 0.05$.

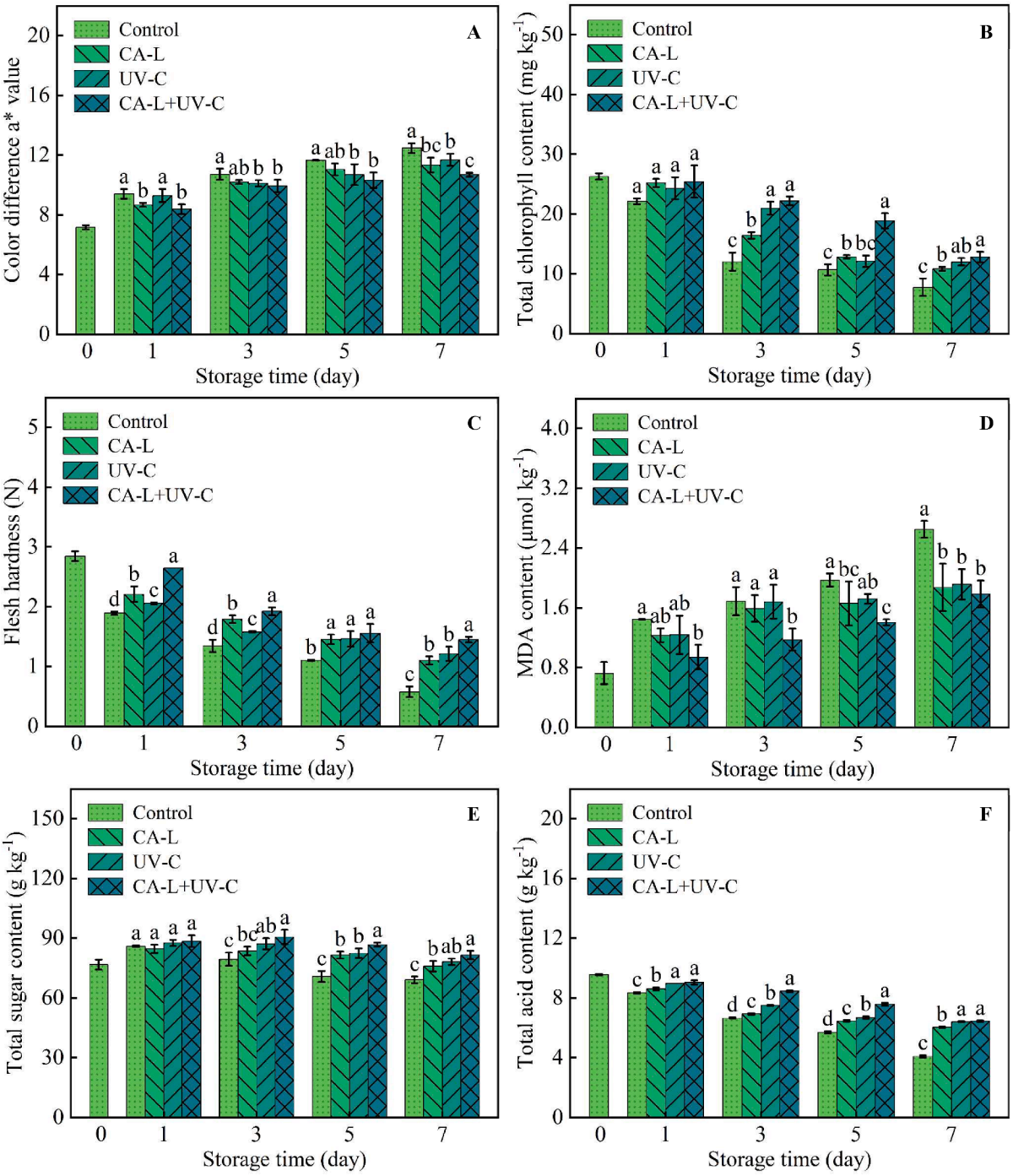

Fig. 2. Effect of CA-L impregnation and UV-C irradiation on color difference a* value (A), total chlorophyll content (B), flesh hardness (C), MDA content (D), total sugar content (E) and total acid content (F) of fresh-cut kiwifruits during one week of storage at 4 ℃. Columns with vertical bars represent the mean ± standard errors of triplicates. Different letters above the vertical bars at the same storage time stand for statistically significant differences at $p < 0.05$.

content was noticed along with the storage time, because sugar was consumed for energy by various metabolic activities. A similar trend has also been reported in the research of Ramazzina et al. (2015) in minimally processed kiwifruits treated by cold plasma. Fig. 2F showed that total acid content gradual decreased with storage time, due to the metabolic process of the fruit, this finding was consistent with kiwifruit slices treated by edible coatings Passafiume et al. (2020) and Benítez et al. (2015). In control group, lowest total acid content was observed at the last day of storage. While for CA-L + UV-C group, it was significantly higher than other groups on day 3 and day 5. In general, these results demonstrated that CA-L and UV-C combined treatment preserved the total sugar and acid content within an acceptable level, possibly due to the joint treatment better retained the intact tissue structure and well adjusted the stress defense response that consumed sugar and acid as substrate in an activated and ordered state.

3.3. *Effect of CA-L and UV-C combined treatment on antioxidant capacity of fresh-cut kiwifruits*

FRAP, total reducing capacity, DPPH and ABTS radical scavenging capacity methods were employed to estimate the antioxidant capacity of fresh-cut kiwifruits. The DPPH and ABTS radical cation can be

scavenged promptly when exposed to proton radical scavengers, and FRAP and total reducing capacity results can reveal the capable to reduce Fe^{3+} to Fe^{2+} by the antioxidants in samples (Yang et al., 2015). As can be observed in Fig. 3A, during the first 3 days of storage, the DPPH radical scavenging capacity increased by 25%, 32%, 39% and 61% in control, CA-L, UV-C and CA-L + UV-C groups, respectively. The results was agree with Mirshekari et al. (2021), who found that CA-L treatment could increase the DPPH radical scavenging capacity of fresh-cut papaya by 36%. Furthermore, Li et al. (2019) also reported that UV-C treatment improved DPPH scavenging capacity of fresh-cut strawberries by 25%. Afterwards, the control group presented a downward trend on DPPH scavenging capacity while it was stabilized in other groups. Similar trend could be observed in ABTS (Fig. 3B), indicating that CA-L and UV-C alone or in combination improved the antioxidant capacity of kiwifruit slices against these two free radicals. For FRAP (Fig. 3C) and total reducing capacity (Fig. 3D), CA-L group showed little differences with control group and they were much lower than UV-C and CA-L + UV-C groups throughout storage, indicating CA-L had few effects on reducing Fe^{3+}, while both UV-C and CA-L + UV-C treatment noticeably enhanced the reducing capacity of Fe^{3+}. In summary, combination of CA-L with UV-C improved the antioxidant capacity of fresh-cut kiwifruit slices, which may be associated with the antioxidant substances in kiwifruit such as AsA, phenols and antioxidant enzymes.

3.4. Effect of CA-L and UV-C combined treatment on the content of AsA, total phenolic and proanthocyanidin of fresh-cut kiwifruits

AsA is a critical nutrient and one of the main antioxidant substances in kiwifruit. As shown in Fig. 4A, the AsA content in all the groups gradually decreased during storage. A sharp decline in control group was observed on day 1, which could be attributed to the oxidative degradation caused by wounding. In contrast, CA-L and UV-C alone or in combination delayed the degradation of AsA, and the joint treatment exhibited almost stable level from day 3 to day 7. Additionally, CA-L treatment inhibited the degradation of AsA better than UV-C during the first 5 days of storage, which was probably caused by the fact that AsA was a photosensitive substance.

Phenols are synthesized when fresh plant tissue is subjected to abiotic stress to protect and heal the mechanical damage from further deterioration (Han et al., 2021). Fig. 4B showed that the total phenolic content elevated first and then slowly decreased in all groups during storage. The increase of total phenolic content was related to the synthesis and accumulation of phenols, while the reduction was probably owing to the massive consumption by oxidation. As one of the vital phenols, the changes of proanthocyanidin content was consistent with the total phenol (Fig. 4C). It was interesting to note that the increment of proanthocyanidins in the CA-L + UV-C group on day 3 was 4, 2 and 1

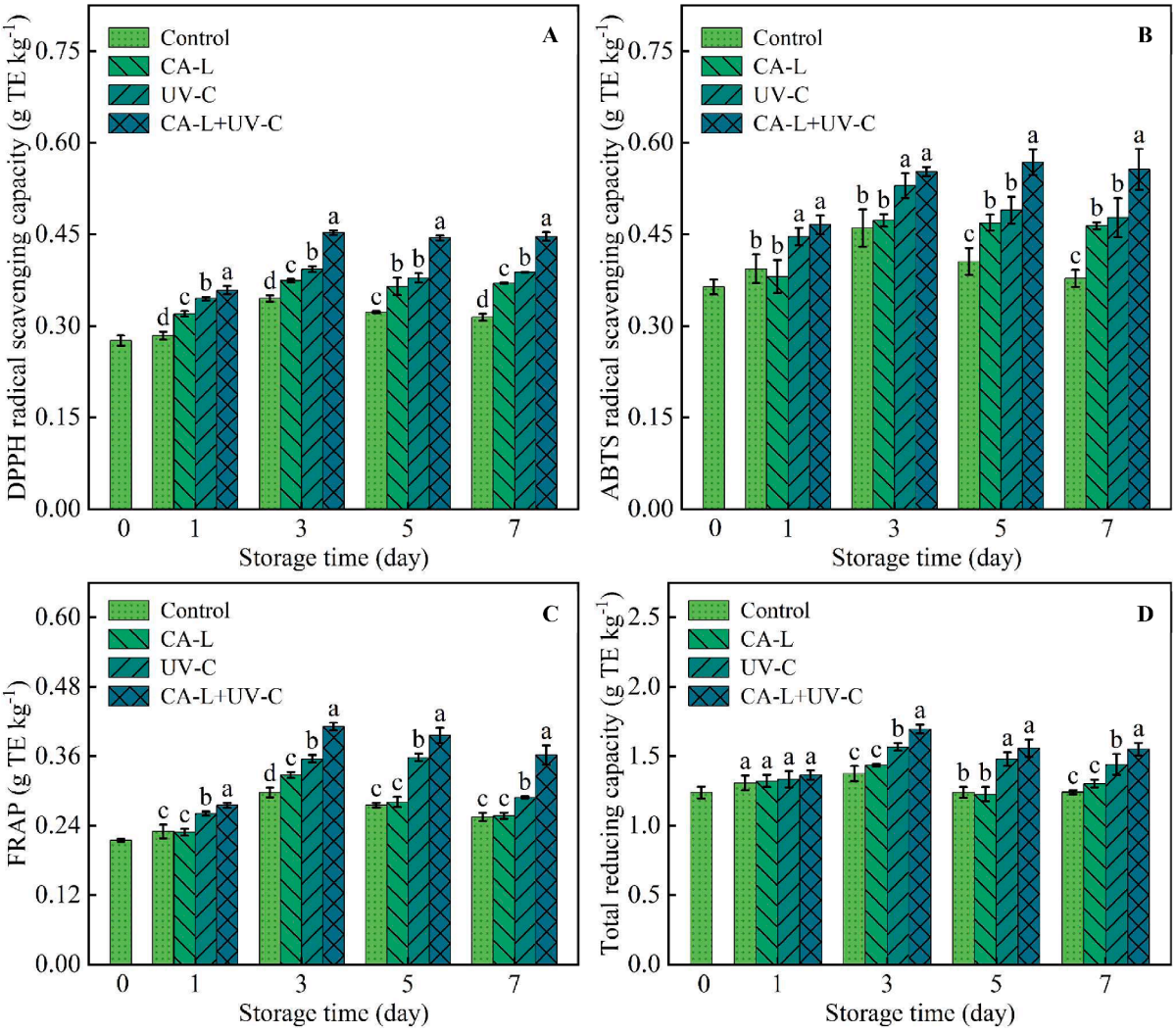

Fig. 3. Effect of CA-L impregnation and UV-C irradiation on DPPH radical scavenging capacity (A), ABTS radical scavenging capacity (B), FRAP (C) and total reducing capacity (D) of fresh-cut kiwifruits during one week of storage at 4 ℃. Columns with vertical bars represent the mean ± standard errors of triplicates. Different letters above the vertical bars at the same storage time stand for statistically significant differences at $p < 0.05$.

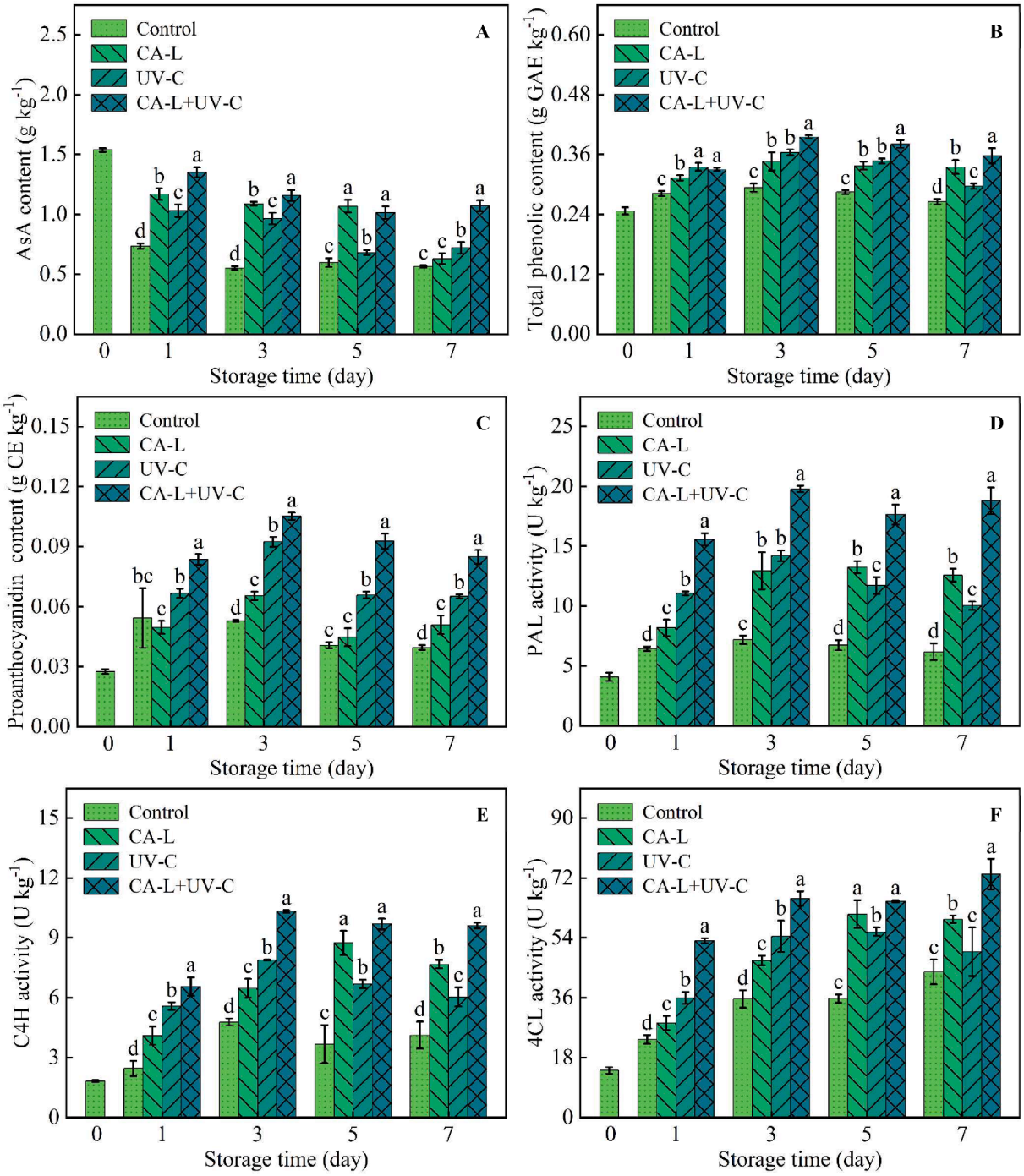

Fig. 4. Effect of CA-L impregnation and UV-C irradiation on AsA content (A), total phenolic content (B), proanthocyanidin content (C), PAL activity (D), C4H activity (E), 4CL activity (F) of fresh-cut kiwifruits during one week of storage at 4 ℃. Columns with vertical bars represent the mean ± standard errors of triplicates. Different letters above the vertical bars at the same storage time stand for statistically significant differences at $p < 0.05$.

times higher than that in the control, CA-L and UV-C groups, respectively. These results indicated that the combination of CA-L and UV-C presented synergistic effects to promote the production of phenols and to conserve it at a rather high level until the end of storage. This increment of phenols by CA-L or UV-C treatments in fresh-cut products was also reported in other studies (Barzegar et al., 2018; Gonzalez-Aguilar et al., 2007; Li et al., 2019; Mirshekari et al., 2021). The elevated phenolic content increased of nutritional value of fresh-cut kiwifruits, and partially illustrated the improvement of antioxidant capacity in Fig. 3.

3.5. Effect of CA-L and UV-C combined treatment on the activity of PAL, C4H and 4CL of fresh-cut kiwifruits

PAL, C4H and 4CL are the pivotal enzymes in phenylpropanoid metabolism pathway, which catalyze the transformation of phenylalanine to phenols in fruits and vegetables (Teoh et al., 2016). As presented in Fig. 4D–F, all of these enzymatic activities were raised dramatically during the first 3 days of storage and then slightly decreased. This trend was consistent with the change in phenolic content, confirming that the enhancement in phenols was due to the elevated enzymatic activity in phenylpropanoid pathway. Teoh et al. (2016) and Li et al. (2021) also

demonstrated that the variation of these enzymes was associated with the changes of phenols. CA-L and UV-C alone or in combination treatments showed higher activities of these enzymes than control throughout storage, and the combined treatment was the highest. At the end of the experiment, PAL, C4H and 4CL activities were activated by 5-fold in both CA-L and UV-C groups. Therefore, the improved activity of these crucial enzymes in phenylpropanoid metabolism might indirectly explain the improved antioxidant capacity in fresh-cut kiwifruits by CA-L and UV-C joint treatment.

3.6. Effect of CA-L and UV-C combined treatment on the activity of SOD, CAT and APX of fresh-cut kiwifruits

Gao et al. (2013) proposed that antioxidant defense systems are composed of antioxidant enzymes (ROS scavenging enzymes) and antioxidants in plants. And SOD, CAT and APX are generally considered as the dominant antioxidant enzymes against ROS in defense systems. SOD catalyzes the conversion of $O_2^{\cdot-}$ into H_2O_2 which is further catalyzed to water by CAT and APX (Gao et al., 2013; Xu et al., 2021). As shown in Fig. 5A, a rising trend in SOD activity along with the storage time was found in all groups. SOD activity in CA-L + UV-C group presented

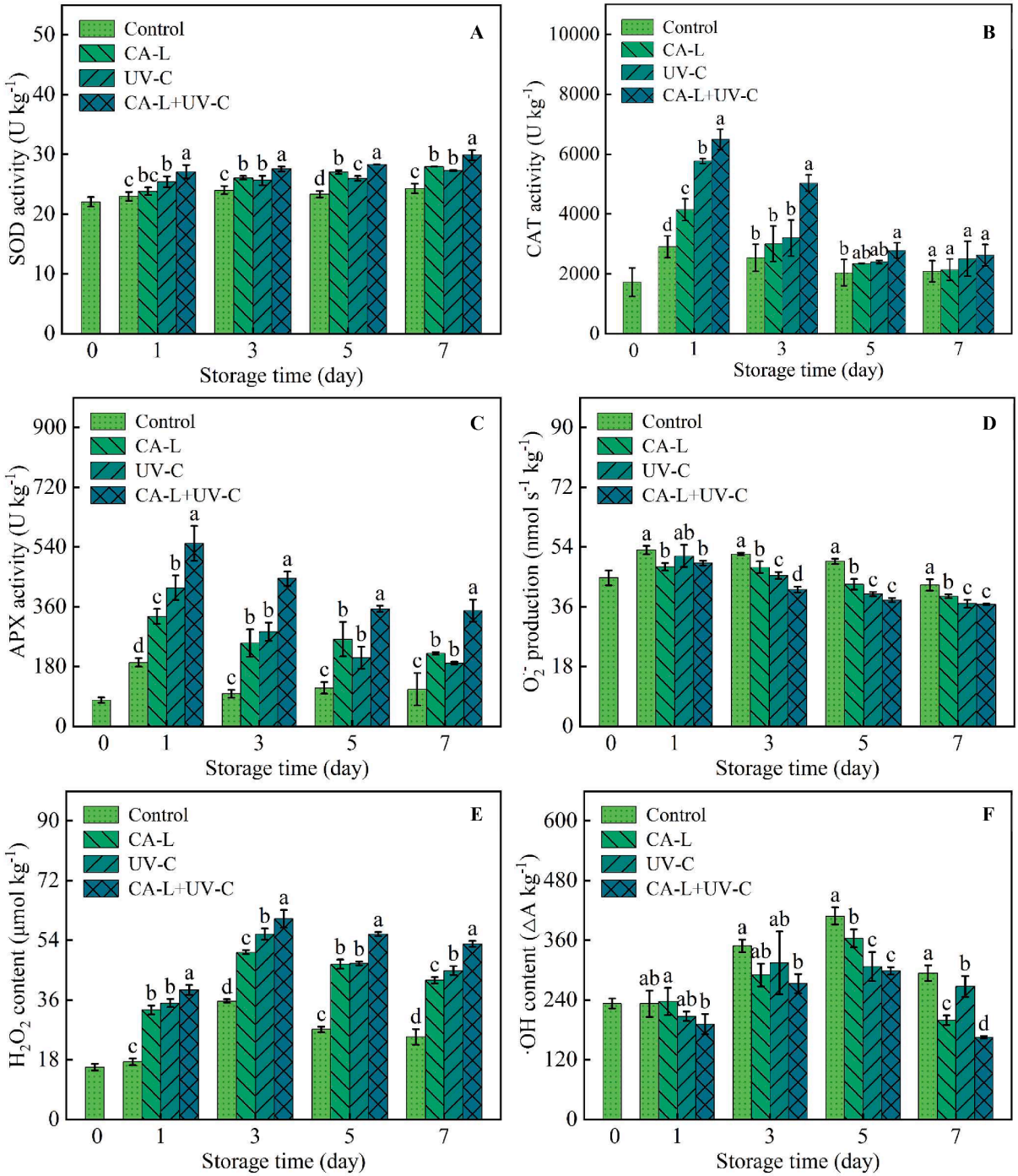

Fig. 5. Effect of CA-L impregnation and UV-C irradiation on SOD activity (A), CAT activity (B), APX activity (C), $O_2^{\cdot-}$ production (D), H_2O_2 content (E) and •OH content (F) of fresh-cut kiwifruits during one week of storage at 4 ℃. Columns with vertical bars represent the mean ± standard errors of triplicates. Different letters above the vertical bars at the same storage time stand for statistically significant differences at $p < 0.05$.

highest level. At the end of storage, the SOD activity was increased by 10%, 27%, 24% and 33% in control, CA-L, UV-C and CA-L + UV-C groups, respectively. Fig. 5B showed that CAT activity was boosted sharply in all groups on the first day then decreased and stabilized on days 5 and 7. CA-L + UV-C group showed considerably higher CAT activity in the first 3 days than other groups. Similar results were also reported in other studies, for example, Mirshekari et al. (2021) reported that dipping fresh-cut papayas with CA-L and hot water enhanced activity of CAT. Li et al. (2019) indicated that UV-C treatment promoted three antioxidant enzymes of strawberry wedges. Meanwhile, Fig. 5C showed that the activity of APX was consistent with the trend of CAT. APX activities in CA-L, UV-C and CA-L + UV-C groups were higher than that in control group throughout storage. Based on these results, it can be assumed that the combination of CA-L and UV-C improved antioxidant defense capacity of kiwifruit by activating the activity of SOD, CAT and APX which can help to eliminate the ROS.

3.7. Effect of CA-L and UV-C combined treatment on the content of $O_2^{\cdot-}$, H_2O_2 and •OH of fresh-cut kiwifruits

It is widely confirmed that the changes in antioxidant enzyme activity are predominantly due to the burst of ROS caused by abiotic stresses (Gao et al., 2013; Xu et al., 2021). As illustrated in Fig. 5D, $O_2^{\cdot-}$ production in all samples increased on day 1 and then gradually decreased. CA-L and UV-C alone or in combination treatments suppressed the production of $O_2^{\cdot-}$ in kiwifruit slices, probably due to the increment of SOD activity in these groups (Fig. 5A). Fig. 5F showed that the level of •OH in the four groups peaked on day 5 and mitigated thereafter. The •OH content was obviously suppressed in CA-L, UV-C and CA-L + UV-C groups and the optimal inhibition effect was detected in the CA-L + UV-C group, probably caused by the higher antioxidant substances in the group. In contrast, from Fig. 5E, the content of H_2O_2 in all groups gradually increased during the first 3 days and then slowly reduced and stabilized on days 5 and 7, the results were consistent with the changes in CAT and APX activity. And higher H_2O_2 content was detected in CA-L, UV-C and CA-L + UV-C groups than that in the control. This phenomenon probably indicated that the increase in H_2O_2 activated the antioxidant enzymes. Additionally, Stone and Yang (2006) interpreted that the elevation of H_2O_2 in plants mediated physiological metabolism as chemical messengers, and further stimulated the phenolic synthesis in the phenylpropanoid metabolism. Li et al. (2019) demonstrated that the increase in H_2O_2 of fresh-cut strawberries treated by UV-C was in accordance with the change in total phenols. And their finding was in agreement with the present study on the relationship between H_2O_2 and phenols. In general, the initial increase in $O_2^{\cdot-}$, H_2O_2 and •OH accumulated the ROS, which then activated the antioxidant enzymes, and improved the antioxidant defense capacity of samples. CA-L + UV-C treatment suppressed the production of $O_2^{\cdot-}$ and •OH, preventing the oxidation of membrane lipid caused by $O_2^{\cdot-}$ and •OH by enhancing the antioxidant enzyme activity and antioxidant content. But the H_2O_2

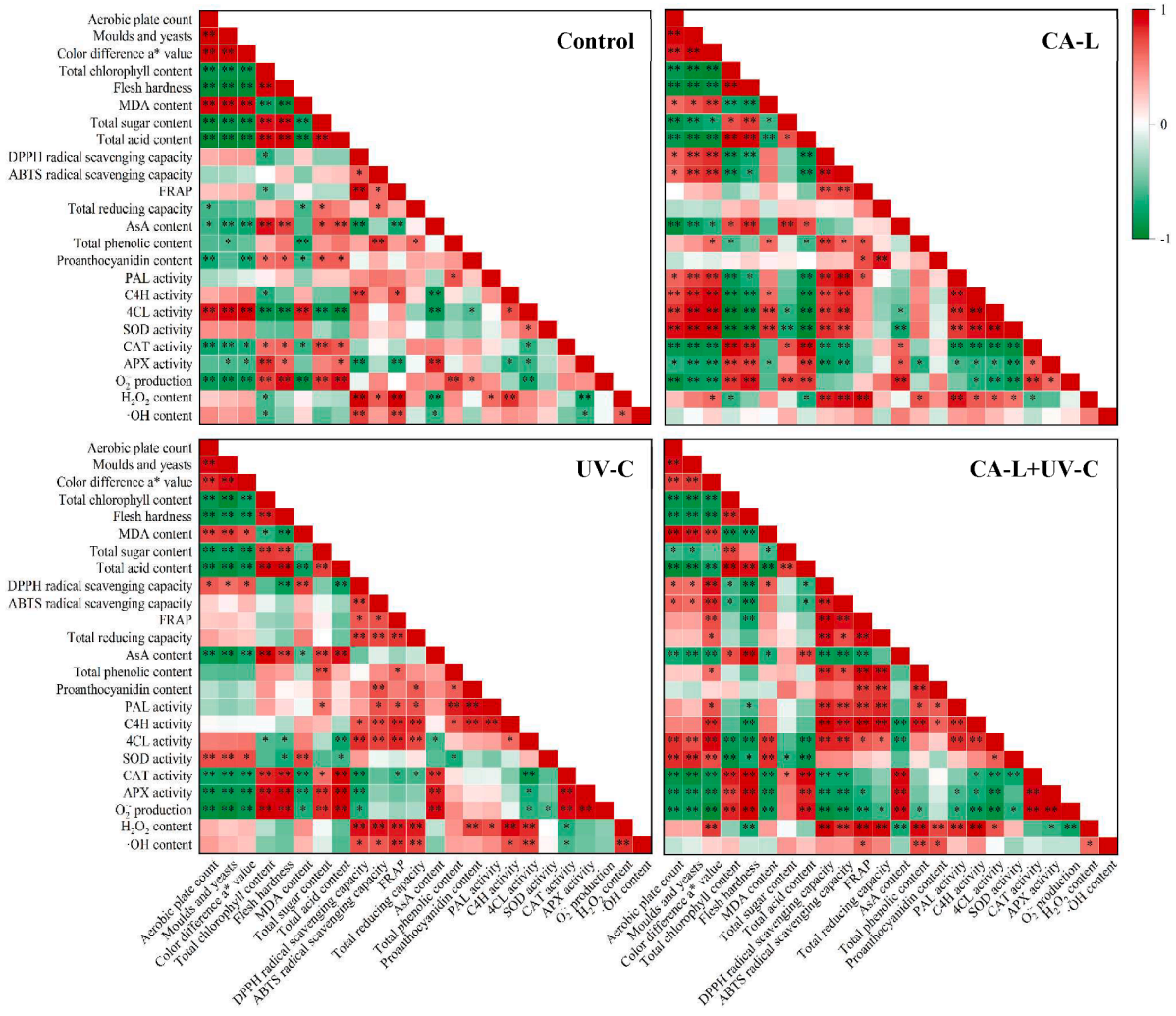

Fig. 6. Pearson correlation analysis matrix of all the parameters investigated of fresh-cut kiwifruits during one week of storage at 4 ℃. Asterisks (*) stand for statistically significant differences at $p < 0.05$ and double asterisk (**) stand for statistically significant differences at $p < 0.01$.

content in CA-L + UV-C group was not suppressed but increased, implying that H_2O_2 was beneficial for the fruit as a messenger substance. However, this benefit effects on the antioxidant capacity of fresh-cut kiwifruits needs to be further explored.

3.8. Correlation analysis

Fig. 6 showed the Pearson correlation analysis matrix to analyze the correlation between the different parameters investigated in this research. High correlations were observed between the quality attributes and antioxidant related indicators, while the parameters differed distinctly among the different treatments. Antioxidant indexes (FRAP, DPPH and ABTS radical scavenging capacity) in each group presented significant correlations at $p < 0.05$ or $p < 0.01$. Therefore, the antioxidant capacity (DPPH scavenging capacity) was adopted as a baseline for correlation comparisons. In the control group, DPPH was positively correlated with C4H, H_2O_2 and •OH, but negatively correlated with total chlorophyll, AsA and APX. In the CA-L group, DPPH was positively correlated with aerobic plate count, moulds and yeasts, a* value, H_2O_2, total phenolic, PAL, C4H, 4CL and SOD, but negatively correlated with total chlorophyll, flesh hardness, total acid, CAT and APX. In the UV-C group, DPPH was positively correlated with aerobic plate count, moulds and yeasts, a* value, C4H and •OH or MDA, 4CL and H_2O_2, but negatively correlated with $O_2^{\cdot-}$, flesh hardness, total acid, CAT and APX. And in the CA-L + UV-C group, DPPH was positively correlated with aerobic plate count, moulds and yeasts, MDA, a* value, H_2O_2, total phenolic, PAL, C4H and 4CL, but negatively correlated with total chlorophyll content, flesh hardness, AsA, CAT, APX and $O_2^{\cdot-}$. Based on these data, the ROS burst activated antioxidant enzyme activity to prevent the excessive accumulation of ROS and oxidation. And the accumulation of phenols was promoted by activating key enzymes in phenylpropanoid metabolism. In addition, highly correlation between H_2O_2 and total phenols was detected, showing the positive regulatory effect of H_2O_2 on the phenylpropane pathway. Consequently, the improved antioxidant defense systems suppressed microbial growth, chlorophyll oxidation and MDA production, and then maintained the safety, color, texture and taste of fresh-cut kiwifruits.

In addition, it is worth mentioning that the PET trays and PVC films applied in this study constitute, in some way, a modified atmosphere packaging. In particular, the PVC films have a certain selective permeability to oxygen, carbon dioxide and water in the air, which may have an influence on the quality properties of the samples. On the one hand, CA-L and UV-C joint treatment maintained the quality of fresh-cut kiwifruits by improving antioxidant defense systems. On the other hand, the packaging materials used in this study may also maintain the quality of samples by improving the microenvironment of storage. Therefore, it is of great necessity to investigate the effect of packaging materials on the storage of fresh-cut kiwifruits to be further researched.

4. Conclusions

In this study, the combination of CA-L impregnation and UV-C irradiation effectively alleviated the microbial load, and better and preserved the overall quality attributes of fresh-cut kiwifruits including color (appearance and chlorophyll content), texture, taste (total sugar and acid), AsA and MDA content when stored at 4 ℃ for 7 d. And the combined treatment improved antioxidant defense capacity by inducing H_2O_2 production to improve the activities of antioxidant enzymes (SOD, CAT and APX), and to activate critical enzymes (PAL, C4H and 4CL) in phenylpropanoid metabolism pathway for catalyzing the accumulation of total phenolic and proanthocyanidin, but the effects of H_2O_2 on the antioxidant defense capacity needs to be further investigated. Furthermore, the $O_2^{\cdot-}$ and •OH were reduced by the combined treatment. In conclusion, the combination of CA-L with UV-C performed excellent synergistic effect on maintaining quality and improving antioxidant capacity of fresh-cut kiwifruits, and the joint treatment has a potential practical application in fresh-cut industry.

CRediT authorship contribution statement

Xiaomin Hu: Investigation, Formal analysis, Methodology, Software, Data curation, Writing – original draft. **Yi Chen:** Investigation, Formal analysis, Methodology. **Xinye Wu:** Investigation, Methodology. **Wenxin Liu:** Investigation, Software. **Xianyu Jing:** Investigation, Data curation. **Yaowen Liu:** Conceptualization, Writing – review & editing. **Jing Yan:** Conceptualization, Supervision, Formal analysis. **Shuxiang Liu:** Conceptualization, Supervision, Formal analysis. **Wen Qin:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Formal analysis, Validation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abd-Elhady, M. (2014). Effect of citric acid, calcium lactate and low temperature prefreezing treatment on the quality of frozen strawberry. *Annals of Agricultural Sciences, 59*(1), 69–75. https://doi.org/10.1016/j.aoas.2014.06.010

Alandes, L., Pérez-Munuera, I., Llorca, E., Quiles, A., & Hernando, I. (2009). Use of calcium lactate to improve structure of "Flor de Invierno" fresh-cut pears. *Postharvest Biology and Technology, 53*(3), 145–151. https://doi.org/10.1016/j.postharvbio.2009.03.006

Arnon, D. I. (1949). Copper enzymes in isolated chloroplasts. Polyphenoloxidase in beta vulgaris. *Plant Physiology, 24*(1), 1–15. https://doi.org/10.1104/pp.24.1.1

Barzegar, T., Fateh, M., & Razavi, F. (2018). Enhancement of postharvest sensory quality and antioxidant capacity of sweet pepper fruits by foliar applying calcium lactate and ascorbic acid. *Scientia Horticulturae, 241*, 293–303. https://doi.org/10.1016/j.scienta.2018.07.011

Beirao-da-Costa, S., Conceicao Moura-Guedes, M., Manuela Ferreira-Pinto, M., Empis, J., & Moldao-Martins, M. (2012). Alternative sanitizing methods to ensure safety and quality of fresh-cut kiwifruit. *Journal of Food Processing and Preservation, 38*(1), 1–10. https://doi.org/10.1111/j.1745-4549.2012.00730.x

Beirao-da-Costa, S., Empis, J., & Moldao-Martins, M. (2014). Fresh-cut kiwifruit structure and firmness as affected by heat pre-treatments and post-cut calcium dips. *Food and Bioprocess Technology, 7*(4), 1128–1136. https://doi.org/10.1007/s11947-013-1151-3

Benítez, S., Achaerandio, I., Pujolà, M., & Sepulcre, F. (2015). Aloe vera as an alternative to traditional edible coatings used in fresh-cut fruits: A case of study with kiwifruit slices. *LWT - Food Science and Technology, 61*(1), 184–193. https://doi.org/10.1016/j.lwt.2014.11.036

Chiabrando, V., Peano, C., & Giacalone, G. (2018). Influence of hot water treatments on postharvest physicochemical characteristics of Hayward and Jintao kiwifruit slices. *Journal of Food Processing and Preservation, 42*(3), 1–9. https://doi.org/10.1111/jfpp.13563

Cisneros-Zevallos, L. (2003). The use of controlled postharvest abiotic stresses as a tool for enhancing the nutraceutical content and adding-value of fresh fruits and vegetables. *Journal of Food Science, 68*, 1560–1565. https://doi.org/10.1111/j.1365-2621.2003.tb12291.x

Duarte-Sierra, A., Tiznado-Hernandez, M. E., Jha, D. K., Janmeja, N., & Arul, J. (2020). Abiotic stress hormesis: An approach to maintain quality, extend storability, and enhance phytochemicals on fresh produce during postharvest. *Comprehensive Reviews in Food Science and Food Safety, 19*(6), 3659–3682. https://doi.org/10.1111/1541-4337.12628

Fenton, H. J. H. (1894). Oxidation of tartaric acid in the presence of iron. *Journal of the Chemical Society, Transactions, 6*(5), 899–910. https://doi.org/10.1039/CT8946500899

Gao, S.-P., Hu, K.-D., Hu, L.-Y., Li, Y.-H., Han, Y., Wang, H.-L., … Zhang, H. (2013). Hydrogen sulfide delays postharvest senescence and plays an antioxidative role in

fresh-cut kiwifruit. *Hortscience, 48*(11), 1385–1392. https://doi.org/10.21273/hortsci.48.11.1385.

Gay, C., & Gebicki, J. M. (2000). A critical evaluation of the effect of sorbitol on the ferric–xylenol orange hydroperoxide assay. *Analytical Biochemistry, 284*, 217–220. https://doi.org/10.1006/abio.2000.4696

GB 2760-2014. (2014). National Standard of the People's Republic of China: National Food Safety Standard, Standards of Food Additives Usage. http://down.foodmate.net/standard/sort/3/42543.html.

George, D. S., Razali, Z., Santhirasegaram, V., & Somasundram, C. (2015). Effects of ultraviolet light (UV-C) and heat treatment on the quality of fresh-cut Chokanan mango and Josephine pineapple. *Journal of Food Science, 80*(2), S426–S434. https://doi.org/10.1111/1750-3841.12762

Gonzalez-Aguilar, G. A., Villegas-Ochoa, M. A., Martinez-Tellez, M. A., Gardea, A. A., & Ayala-Zavala, J. F. (2007). Improving antioxidant capacity of fresh-cut mangoes treated with UV-C. *Journal of Food Science, 72*(3), S197–S202. https://doi.org/10.1111/j.1750-3841.2007.00295.x

Han, C., Zhen, W., Chen, Q., & Fu, M. (2021). UV-C irradiation inhibits surface discoloration and delays quality degradation of fresh-cut stem lettuce. *LWT - Food Science and Technology, 147*, Article 111533. https://doi.org/10.1016/j.lwt.2021.111533

Hanson, E. J., Beggs, J. L., & Beaudry, R. M. (1993). Applying calcium chloride postharvest to improve highbush blueberry firmness. *Hortscience, 28*(10), 1033–1034. https://doi.org/10.21273/hortsci.28.10.1033.

Hodges, D. M., DeLong, J. M., Forney, C. F., & Prange, R. K. (1999). Improving the thiobarbituric acid-reactive-substances assay for estimating lipid peroxidation in plant tissues containing anthocyanin and other interfering compounds. *Planta, 207*(4), 604–611. https://doi.org/10.1007/s004250050524

Leyva, A., Quintana, A., Sánchez, M., Rodríguez, E. N., Cremata, J., & Sánchez, J. C. (2008). Rapid and sensitive anthrone̊ sulfuric acid assay in microplate format to quantify carbohydrate in biopharmaceutical products: Method development and validation. *Biologicals, 36*(2), 134–141. https://doi.org/10.1016/j.biologicals.2007.09.001

Li, L., Li, C., Sun, J., Xin, M., Yi, P., He, X., … Tang, J. (2021). Synergistic effects of ultraviolet light irradiation and high-oxygen modified atmosphere packaging on physiological quality, microbial growth and lignification metabolism of fresh-cut carrots. *Postharvest Biology and Technology, 173*, Article 111365. https://doi.org/10.1016/j.postharvbio.2020.111365

Li, M., Li, X., Han, C., Ji, N., Jin, P., & Zheng, Y. (2019). UV-C treatment maintains quality and enhances antioxidant capacity of fresh-cut strawberries. *Postharvest Biology and Technology, 156*, Article 110945. https://doi.org/10.1016/j.postharvbio.2019.110945

Li, S., Zhang, L., Liu, M., Wang, X., Zhao, G., & Zong, W. (2017). Effect of poly-ε-lysine incorporated into alginate-based edible coatings on microbial and physicochemical properties of fresh-cut kiwifruit. *Postharvest Biology and Technology, 134*, 114–121. https://doi.org/10.1016/j.postharvbio.2017.08.014

Luna-Guzmán, I., & Barrett, D. M. (2000). Comparison of calcium chloride and calcium lactate effectiveness in maintaining shelf stability and quality of fresh-cut cantaloupes. *Postharvest Biology and Technology, 19*(1), 61–72. https://doi.org/10.1016/s0925-5214(00)00079-x

Ma, L., Zhang, M., Bhandari, B., & Gao, Z. (2017). Recent developments in novel shelf life extension technologies of fresh-cut fruits and vegetables. *Trends in Food Science & Technology, 64*, 23–38. https://doi.org/10.1016/j.tifs.2017.03.005

Martin-Diana, A. B., Rico, D., Frias, J. M., Barat, J. M., Henehan, G. T. M., & Barry-Ryan, C. (2007). Calcium for extending the shelf life of fresh whole and minimally processed fruits and vegetables: A review. *Trends in Food Science & Technology, 18*(4), 210–218. https://doi.org/10.1016/j.tifs.2006.11.027

Mastromatteo, M., Mastromatteo, M., Conte, A., & Del Nobile, M. A. (2011). Combined effect of active coating and MAP to prolong the shelf life of minimally processed kiwifruit (Actinidia deliciosa cv. Hayward). *Food Research International, 44*(5), 1224–1230. https://doi.org/10.1016/j.foodres.2010.11.002

Mirshekari, A., & Madani, B. (2021). Effects of hot water and calcium lactate treatments on fresh-cut quality of papaya. *Journal of Horticulture and Postharvest Research, 4*(Special Issue-Fresh-cut Products), 81–90. https://doi.org/10.22077/jhpr.2021.4721.1242

Naser, F., Rabiei, V., Razavi, F., & Khademi, O. (2018). Effect of calcium lactate in combination with hot water treatment on the nutritional quality of persimmon fruit during cold storage. *Scientia Horticulturae, 233*, 114–123. https://doi.org/10.1016/j.scienta.2018.01.036

Passafiume, R., Gaglio, R., Sortino, G., & Farina, V. (2020). Effect of three different aloe vera gel-based edible coatings on the quality of fresh-cut "hayward" kiwifruits. *Foods, 9*(7), 1–17. https://doi.org/10.3390/foods9070939

Prajapati, U., Asrey, R., Varghese, E., & Sharma, R. R. (2021). Effects of calcium lactate on postharvest quality of bitter gourd fruit during cold storage. *Physiology and Molecular Biology of Plants, 27*(8), 1811–1821. https://doi.org/10.1007/s12298-021-01045-8

Ramazzina, I., Berardinelli, A., Rizzi, F., Tappi, S., Ragni, L., Sacchetti, G., & Rocculi, P. (2015). Effect of cold plasma treatment on physico-chemical parameters and antioxidant activity of minimally processed kiwifruit. *Postharvest Biology and Technology, 107*, 55–65. https://doi.org/10.1016/j.postharvbio.2015.04.008

Shen, X., Zhang, M., Devahastin, S., & Guo, Z. (2019). Effects of pressurized argon and nitrogen treatments in combination with modified atmosphere on quality characteristics of fresh-cut potatoes. *Postharvest Biology and Technology, 149*, 159–165. https://doi.org/10.1016/j.postharvbio.2018.11.023

Stone, J. R., & Yang, S. (2006). Hydrogen peroxide: A signaling messenger. *Antioxidants & Redox Signaling, 8*(3–4), 243–270. https://doi.org/10.1089/ars.2006.8.243

Sun, B., Leandro, C., Ricardo da Silva, J. M., & Spranger, I. (1998). Separation of grape and wine proanthocyanidins according to their degree of polymerization. *Journal of Agricultural and Food Chemistry, 46*(4), 1390–1396. https://doi.org/10.1021/jf970753d

Teoh, L. S., Lasekan, O., Adzahan, N. M., & 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. https://doi.org/10.1016/j.postharvbio.2016.06.008

Wang, D., Chen, L., Ma, Y., Zhang, M., Zhao, Y., & Zhao, X. (2019). Effect of UV-C treatment on the quality of fresh-cut lotus (Nelumbo nucifera Gaertn.) root. *Food Chemistry, 278*, 659–664. https://doi.org/10.1016/j.foodchem.2018.11.102

Wang, S., Qiu, Y., & Zhu, F. (2021). Kiwifruit (Actinidia spp.): A review of chemical diversity and biological activities. *Food Chemistry, 350*, Article 128469. https://doi.org/10.1016/j.foodchem.2020.128469

Xu, D., Gu, S., Zhou, F., Hu, W., Feng, K., Chen, C., & Jiang, A. (2021). Mechanism underlying sodium isoascorbate inhibition of browning of fresh-cut mushroom (Agaricus bisporus). *Postharvest Biology and Technology, 173*, Article 111357. https://doi.org/10.1016/j.postharvbio.2020.111357

Yang, M., Shen, Q., Li, L.-Q., Huang, Y.-Q., & Cheung, H.-Y. (2015). Phytochemical profiles, antioxidant activities of functional herb abrus cantoniensis and abrus mollis. *Food Chemistry, 177*, 304–312. https://doi.org/10.1016/j.foodchem.2015.01.054