Food Packaging and Shelf Life 31 (2022) 100816

Contents lists available at ScienceDirect

Food Packaging and Shelf Life

journal homepage: www.elsevier.com/locate/fpsl

Evaluation of the anti-browning effect of quercetin on cut potatoes during storage

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ARTICLE INFO

Keywords:
Fresh-cut potato
Enzyme activity
Minimally process
Trans-cinnamic acid
Quercetin

ABSTRACT

The effects of quercetin treatment on enzymatic and oxidative activity, color quality and phenolic compound content of fresh-cut potatoes were investigated. To determine the effective anti-browning amount of quercetin, color change with storage was examined by making a preliminary experiment. At the end of the preliminary trial, it was determined that 25 mg/100 mL quercetin treatment kept the browning index (BI) value significantly low ($p < 0.05$). It was determined that this amount of quercetin treatment inhibited PPO and PAL activities, and decreased the formation of MDA and accumulation of phenolic compounds. The results showed that quercetin played an important role in preventing enzymatic browning, extending shelf life and maintaining quality in fresh-cut potatoes.

1. Introduction

Potato (*Solanum tuberosum L.*) is the sixth-largest food crop worldwide and is a good source of nutrients and phytochemicals (FAOSTAT, 2021). The fast-paced new lifestyle has increased demand for ready-to-eat food by over 30% in the last 10 years (Liu et al., 2018). Consumers demand minimally processed and healthy ready-to-eat food, and fresh-cut products are the reason for preference at this point. But the cutting inevitably exposes tissue to injury stress, which can accelerate deterioration processes such as water loss, oxidative browning, tissue softening and development of off-flavors, thereby limiting the shelf life of fresh-cut produce (Zhang et al., 2020) The liberated polyphenol oxidase (PPO) initiates browning reactions by converting phenolic compounds to o-quinones, which then polymerize into dark melanin pigments (Friedman, 1996). Browning is the main factor restricting the market value of fresh-cut products as it negatively affects consumer preference (Gao, Wu, Zeng, Li, & Guan, 2018).

Since phenolic compounds are the substrate of PPO, they play a role in the quality loss of fresh-cut potatoes. The major phenolic compound in potatoes is chlorogenic acid (Valiñas, Lanteri, ten Have, & Andreu, 2017). Phenylalanine ammonia-lyase (PAL) initiates the formation pathway of phenolic compounds by converting L-phenylalanine to trans-cinnamic acid (Ranjitha et al., 2017). Therefore, PAL is another key enzyme that indirectly causes enzymatic browning (Liu et al., 2018).

In recent years, there has been a trend towards natural agents that have a positive effect on health and prevent browning in line with the demands of consumers. To prevent enzymatic browning in fresh-cut fruit and vegetables, studies were carried out on the use of natural agents such as phenolic acids, flavonoids, thiol compounds, organic acids, bioactive peptides and plant extracts (Cheng et al., 2020; Kasnak, 2020; Klimczak & Gliszczyńska-Świgło, 2017; Liu et al., 2018; Palamutoğlu, 2020; Peng et al., 2014; Sukhonthara, Kaewka, & Theerakulkait, 2016; Tinello & Lante, 2017).

Quercetin (3,3,4′,5,7-pentahydroxyflavone) is a flavonoid containing a double bond between positions 2 and 3 and oxygen at position 4 of the heterocyclic C ring (Fig. 1). Quercetin's reported health-protective effects include anti-inflammation, anti-apoptosis, immune protection, and anti-cancer (Chen et al., 2021). In addition, quercetin is a powerful antioxidant. It provides strong tolerance to various biotic and abiotic stresses in plants (Singh, Arif, Bajguz, & Hayat, 2021). In a study, it was reported that quercetin inhibited PPO competitively (Chen & Kubo, 2002). In another study, it was reported that onion by-products had a PPO inhibitory effect, and this effect might be associated with the thiol compounds and quercetin contained in the onion (Roldán, Sánchez-Moreno, de Ancos, & Cano, 2008). However, no study has been found examining the physical and chemical changes that may occur by treating with pure quercetin of fresh-cut products. Therefore, we investigated the anti-browning characteristics of quercetin in fresh-cut

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https://doi.org/10.1016/j.fpsl.2022.100816
Received 27 July 2021; Received in revised form 10 January 2022; Accepted 19 January 2022
Available online 21 January 2022

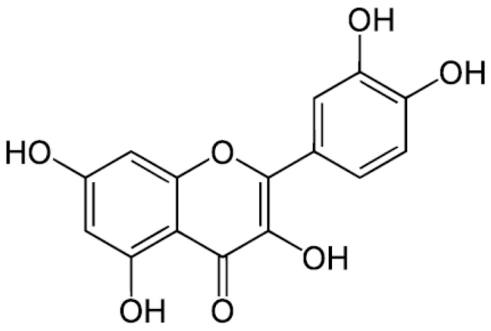

Fig. 1. Chemical structure of quercetin.

potato through the assessment of BI, PPO, PAL, malondialdehyde (MDA), phenolic content and other related indicators.

2. Materials and methods

2.1. Plant material

Potatoes (*Solanum tuberosum* cv. Agria) were taken from a local market at Afyonkarahisar, Turkey; all were of uniform size and without mechanical harm. Selected potatoes were washed and dried at room temperature, prior to processing.

2.2. Determination of the most effective quercetin concentration on BI

Potatoes were peeled and cut into 1 cm thick elliptical shapes to be used for color determination only. Elliptical potato slices were immediately immersed in water, ascorbic acid solution and different concentrations of quercetin solutions [10 mg/100 mL quercetin (Q10), 25 mg/100 mL quercetin (Q25), 50 mg/100 mL quercetin (Q50), 75 mg/100 mL quercetin (Q75), and 100 mg/100 mL quercetin (Q100)] for 10 min. Potato slices were then air dried, placed in polyethylene containers and stored at 4 °C for 7 days. The color analyzes were performed by taking samples at certain periods during storage. The most effective quercetin concentration in keeping the BI value low was determined and this concentration was used in other analyses.

2.3. Treatments

Potato samples were peeled and cut into cubes with a thickness of 1 cm (±0.25). Three different treatment groups were formed as control (water), quercetin (25 mg/100 mL effective quercetin concentration determined by BI results) and ascorbic acid (AA) (0.5 g/100 mL). The fresh-cut samples from five different tubers were immersed in these solutions for 10 min and dried at room temperature. After this, they were placed into polyethylene containers and stored at 4 °C for 8 days. Samples were taken after cutting (day 0) and day 1, day 3, day 6, day 8 during storage. Each sample was obtained from five different tuber pieces from each treatment group, and three replicate runs were performed for each sample.

2.4. Measurement of color and weight loss (WL)

The colors of potato slices were analyzed using a handheld spectrophotometer (Ci64/X-rite/USA). The color was expressed using Hunter scale parameters L^* for the lightness from black (0) to white (100), a^* from green (−) to red (+), and b^* from blue (−) to yellow (+). Color changes in samples were determined by monitoring changes in L^*, a^*, and b^*. Browning index was calculated with the following formula (Palou & Swanson, 1999).

$$BI = \frac{[100(x - 0,31)]}{0.172} \quad (1)$$

$$where \quad x = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 3.012b^*)}$$

For weight loss determination, each treatment group was formed from five cubic pieces cut from different potato tubers. The samples placed in polyethylene containers were stored for 8 days. During the storage period, the samples were weighed at certain intervals, and the percent weight loss was calculated.

2.5. Measurement of enzyme activity

Potato samples (1 g) were homogenized in 10 mL cold potassium phosphate buffer (0.1 M, pH 6.5, 4 °C) for PPO determination, in 10 mL cold borate buffer (0.2 M, pH 8.8, 4 °C) for PAL determination during 3 min. The homogenates were centrifuged (Nuve NF 800R) at 16000xg for 15 min and 4 °C. The supernatants were used for the enzyme assays.

PPO activity was measured by the method of Kasnak (2020). The supernatant (0.25 mL) was mixed with 0.75 mL potassium phosphate buffer (0.1 M, pH 5.8) and 0.50 mL catechin hydrates (20 mM). The mixture was read on the spectrophotometer (Thermo Genesys 150) at 410 nm. The absorbance was measured every 30 s for a total of 2 min. The PPO activity was calculated on a fresh weight basis as U/g, where U = 0.001 $\Delta A_{410\ nm}$ per min.

PAL activity was measured following a modified method of Gao, Zeng, Ren, Li, and Xu (2018). The supernatant (0.2 mL), borate buffer (1.28 mL) and phenylalanine solution (0.4 mL 50 mM) were stirred. The mixture was incubated at 30 °C for 30 min. After 30 min, the absorbance of the mixture was read at 290 nm using the UV–visible spectrophotometer. The results were expressed as milligrams of trans-cinnamic acid using a standard calibration curve of trans-cinnamic acid.

2.6. Measurement of MDA and hydrogen peroxide (H_2O_2)

MDA and H_2O_2 content of samples was determined according to Zheng, Liu, Liu, Liu, and Zheng (2019), with small modifications. The potato sample (1 g) was homogenized with 10 mL of 1 g/L of pre-cooled trichloroacetic acid and centrifuged at 3007×*g* for 15 min. Supernatants were used in MDA and H_2O_2 analysis.

In MDA analysis, 0.6 mL of supernatant and 1 mL of thiobarbituric acid (6.7 g/L) were mixed in glass tubes and incubated at 95 °C for 20 min. The mixture was cooled with running water. The absorbance of the mixture was measured at 450, 532, and 600 nm. Eq. 2 was used to reckon MDA content:

$$\text{MDA content } (\mu mol/kg) = 6.45 \times (OD_{532} - OD_{600}) - 0.56 \times OD_{450} \quad (2)$$

For determination of H_2O_2 content, 0.6 mL of the filtrate, 1 mL of 1 M potassium iodide and 1 mL of 10 mM potassium phosphate buffer (pH 7) were mixed and read at 390 nm on the spectrophotometer against the blank. The results were determined in mmol H_2O_2 /kg fresh weight.

2.7. Measurement of phenolic compound and antioxidant activity

The potato tissue (1 g) was homogenized in 10 mL of pure methanol. The mixture was centrifuged at 3007xg for 15 min and residues were re-extracted twice. After centrifugation, the supernatants were mixed and used as a crude extract to determine the antioxidant activity and phenolic compounds.

For the determination of total phenolic content (TPC), 0.25 mL of the crude extract was mixed with 0.25 mL Folin-Ciocalteu reagent, 3.5 mL pure water and 1 mL 20% sodium carbonate. After the mixture had been kept for incubation at 25 °C in the water bath (Nuve BM 402) for 1 h, absorbance was read at 720 nm using a UV–visible spectrophotometer (Kaur & Kapoor, 2002). The results were expressed in mg catechin/kg fresh weight.

Phenolic compounds of samples were analyzed according to the

method of Albishi, John, Al-Khalifa, and Shahidi (2013) with slight modification. HPLC analysis was performed using a Thermo Scientific HPLC Dionex Ultimate 3000 system equipped with an automatic injector WPS-3000SL, TCC-3000SD column oven and an MWD-3000 Multiple Wavelength photodiode array detector. A column C18 (250 * 4.6 mm ID, 5 μm particle size) was used. The mobile phase used was 1% formic acid in purified water (A) vs 100% methanol (B) and the following gradient program was performed: (B) = 5% (0–5 min), 50% (5.1–10 min), 70% (10.1–15 min), 80% (15.1–20 min), and 100% (20.1–25 min). The crude extract (20 μL) was injected into the column. The flow rate was 1.5 mL/min and the column temperature was 35 °C. Chlorogenic acid (CHA) and ferulic acid (FA) peaks at 280 nm, caffeic acid (CA) and trans-cinnamic acid (TCA) peaks were read at 320 nm.

The antioxidant activity was determined using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging method with slight modification (Brand-Williams, Cuvelier, & Berset, 1995). DPPH solution (0.4 mL, 20 mM) and crude extract (1.6 mL) were mixed and left in dark for 30 min incubation at room temperature. The absorption values of the mixture were read on the spectrophotometer at a wavelength of 517 nm, and antioxidant activities were calculated using the formula:

$$\text{Antioxidant activity } (\%) = (1 - A_{sample}/A_{methanol}) \times 100 \quad (3)$$

2.8. Statistical analysis

The data were expressed as means ± standard deviations and subjected to analysis of variance using the SPSS version 23 software package (IBM Corp., Armonk, NY, USA). The Duncan multiple comparison test at $\alpha = 0.05$ was used to compare means among treatments. Pearson's correlation test was used to determine the relationship of dependent variables with each other.

3. Result and discussion

3.1. Effect of quercetin on color and weight loss of potatoes

Color is considered an important parameter reflecting quality in fresh-cut products. To determine the optimal concentration of quercetin on the quality of fresh-cut potato, five quercetin concentrations were studied. Water and air were used as controls and ascorbic acid was used as a positive control. In Fig. 2, changes in L^*, a^*, b^*, and BI values of all samples with storage are shown. Except for Q10, samples treated with quercetin were seen to have a higher L^* value and lower a^* value compared to the control samples during storage. A high L^* value means a high brightness and is positive for the appeal of the product. Low a^* value means less enzymatic browning as the redness is low. Quercetin concentrations showed a strong positive correlation with the L^* value (0.416**) and a strong negative correlation with the a^* value (−0.448**). However, since the color of the quercetin was yellow, the b * value of the samples treated with quercetin was high compared to

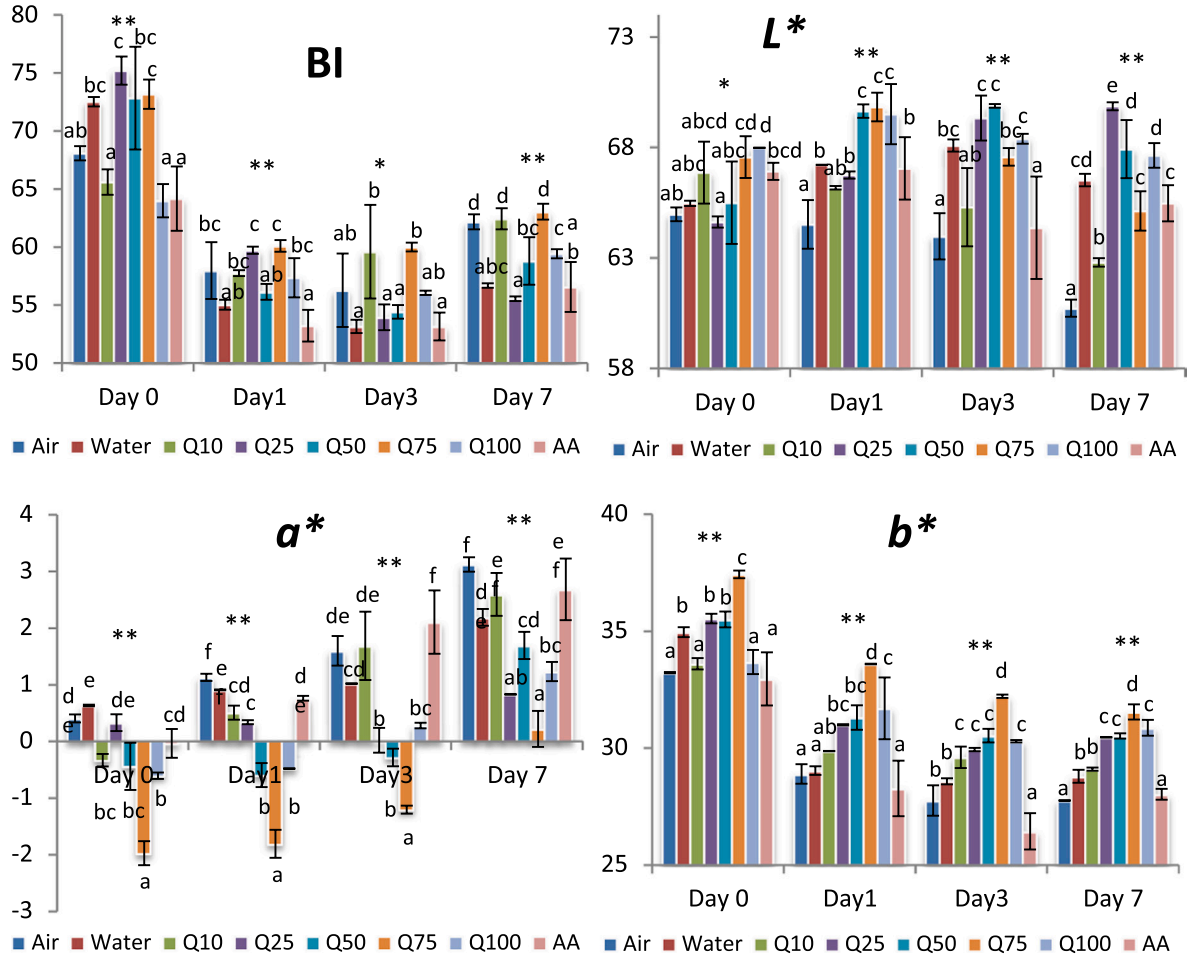

Fig. 2. Effects of quercetin treatment on the L*, a*, b* and BI values of fresh-cut potatoes during storage. Different lowercase letters indicate significant differences ($\alpha = 0.05$) according to the Duncan multiple comparison test ($p < 0.05$). Error bars represent standard deviations. Nd:no difference, * $p < 0.05$, ** $p < 0.01$, BI: browning index.

other treatments. The higher weight of the b* value compared to the a* value in the BI formula increased the BI value of the samples treated with quercetin. However, the BI value of Q25 was significantly lower than all other samples ($p < 0.05$). Based on these results, 25 mg/100 mL can be considered as the optimal concentration of quercetin that is effective in controlling browning and maintaining the quality of fresh-cut potato.

A significant decrease in the weights of all treatments was determined during the storage period ($p < 0.01$). The highest weight loss was observed in the control group with 2.31%, followed by the quercetin group with 2.04% and the ascorbic acid group with 1.36%, respectively. At the end of storage, the weight losses of the treatment groups differed significantly from each other ($p < 0.05$). In a study, it was reported that the weight loss of cut apples treated with UV was 12.2% after 15 days of storage, and 19.1% in the control group (Chen, Hu, He, Jiang, & Zhang, 2016).

Weight loss in fresh-cut products is caused by evaporation of moisture content and loss of nutrients (Azhar Shapawi, Ariffin, Shamsudin, Mohamed Amin Tawakkal, & Gkatzionis, 2021). The way to prevent weight loss is to slow down the respiratory rate. Because as a result of energy production from glucose with respiration, carbohydrate loss and water transpiration occur. It was reported that AA treatment was able to suppress the increase in respiratory rate and reduce weight loss after potato slices were cut (F. Zhou et al., 2021). To slow down the respiratory rate in cut potatoes, it is necessary to prevent the breakdown of starch into simple sugars such as glucose and maltose. Quercetin delays the breakdown of starch by directly inhibiting alpha-amylase and forming a barrier to starch-degrading enzymes as a result of its interaction with starch (Y. Zhou, Jiang, Mak, & Zhou, 2021). Therefore, quercetin reduces the loss of moisture and nutrients caused by respiration.

3.2. Effect of quercetin on PPO and PAL activity of potatoes

PPO can catalyze the hydroxylation of monophenols to o-diphenols and oxidation of o-diphenols to o-quinones, which will then polymerize and form dark pigment melanin (Lim & Wong, 2018). In Fig. 3, the effect of all treatments on PPO and PAL is given. As seen in Fig. 3, PPO activity on the initial day was significantly lower in quercetin and AA treatments than in the control ($p < 0.05$). There was no statistically significant difference between the treatments on day 1, day 3 and day 6. At the end of storage (day 8), it was observed that quercetin treatment significantly reduced PPO activity compared to control and AA ($p < 0.05$). This result indicates that the shelf life of cut potatoes treated with quercetin is longer than that of the others. Because PPO activity reduces shelf life by causing tissue softening as a result of oxidation and accelerating microbial spoilage. Cheng et al. (2020) reported that chlorogenic acid treatment in fresh-cut potato inhibits the PPO enzyme and prevents enzymatic browning. Palamutoğlu (2020) reported that whey protein treatment inhibited PPO activity in fresh-cut cubic potatoes. It was reported that treatment of pear puree samples with ascorbic acid was the most effective treatment in controlling browning compared to treatments with other organic acids (citric acid, ferulic acid and salicylic acid), and on the contrary, it was the least effective treatment in inhibiting PPO activity (Liao et al., 2020).

PAL plays a significant role in enzymatic browning by catalyzing the substrate accumulation in the phenylalanine pathway (Zhu et al., 2021). PAL increases the phenolic content by converting L-phenylalanine to

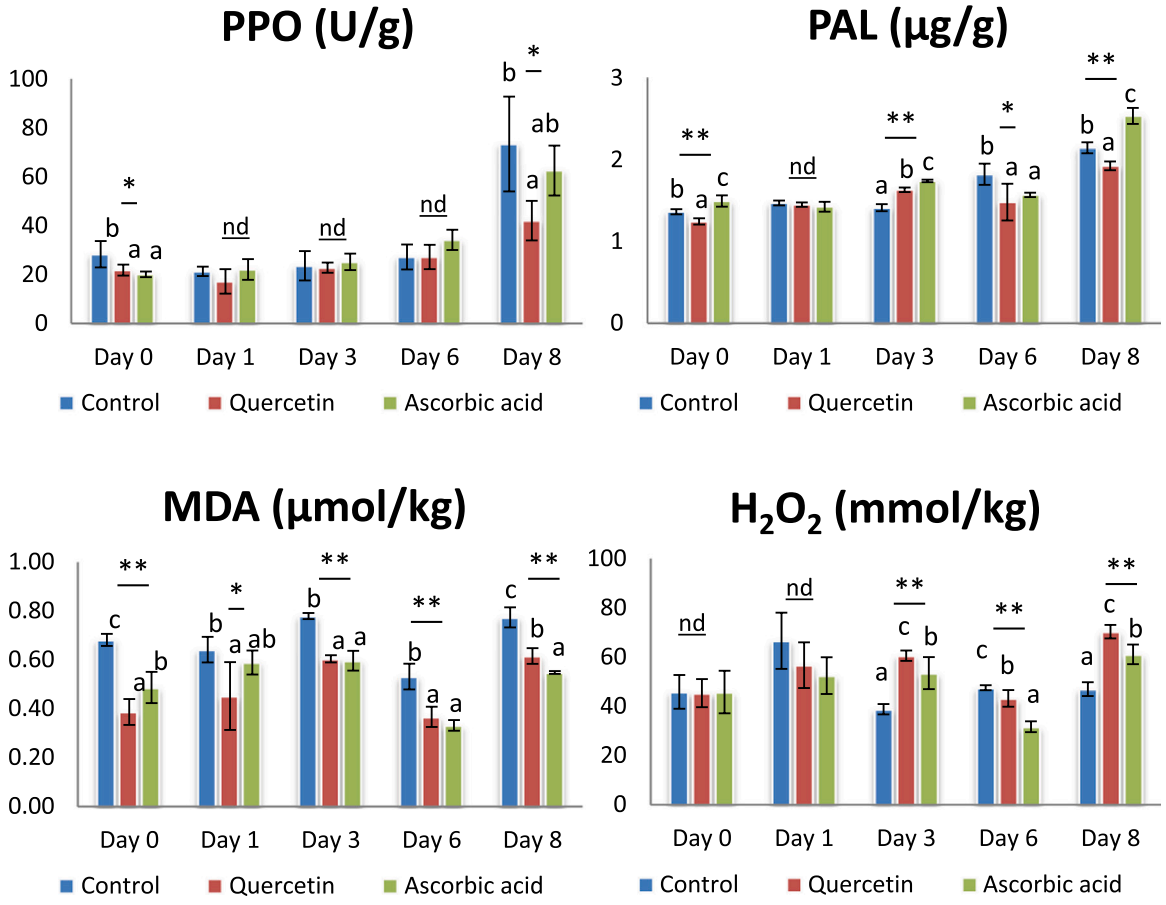

Fig. 3. The effects of quercetin on PPO, PAL, MDA and H_2O_2 of fresh-cut potatoes during storage time. Different lowercase letters indicate significant differences ($\alpha = 0.05$) according to the Duncan multiple comparison test ($p < 0.05$). Error bars represent standard deviations. Nd:no difference, * $p < 0.05$, ** $p < 0.01$, PPO: polyphenol oxidase, PAL: phenylalanine ammonia-lyase, MDA: malondialdehyde, H_2O_2: hydrogen peroxide.

trans-cinnamic acid, which serves as a pioneer for diverse phenolic compounds such as chlorogenic acid, protocatechuic acid, caffeic acid and di-caffeoyl tartaric acid (Ranjitha et al., 2017; Wang et al., 2015). As seen in Fig. 3, the PAL activity of the quercetin treatment at the beginning and end of storage was significantly lower than PAL activities in other treatments ($p < 0.01$). The phenylpropanoid mechanism that results in flavonoid formation can be expected to remain lower in tubers treated with quercetin. Therefore, lower PAL activity will lead to the formation of lower trans-cinnamic acid, the accumulation of phenolic compounds, which are the substrate of PPO, will be reduced and extend shelf life. Significant positive correlations were found between PAL activity and PPO, CHA, CHA and TPC (Table 1). There was an increase in PAL activity of all treatments except a decrease at day 6 during storage time. Cantos, Tudela, Gil, and Espín (2002) believed that the browning development during the first 4 days in fresh-cut potatoes was mainly correlated to PAL activity rather than PPO or POD activity. Zhu et al. (2021) reported that PAL activity increased in the first 4 days and decreased in the next 4 days in ultrasound-purslane extract combination treatments of fresh-cut potatoes. In another study, it was reported that the PAL activity of the group treated with GABA in cut potatoes was lower than the control during storage time (Gao, Zeng et al., 2018).

3.3. Effect of quercetin on MDA and H_2O_2 content of potatoes

The occurrence of MDA is an important indicator of the oxidative damaged cells under stress (Li et al., 2011). The change of MDA and H_2O_2 activities of the treatments during storage is shown in Fig. 3. During the storage period, the MDA content of the quercetin and AA treated samples remained significantly lower compared to the control ($p < 0.01$). The MDA content of the samples treated with quercetin on Day 0 ($p < 0.01$) and Day 1 ($p < 0.05$) remained significantly lower than samples treated with AA. Only at the end of storage, the AA treatment significantly outperformed quercetin in keeping the MDA content low ($p < 0.05$). Treatment with quercetin was as successful as AA in keeping MDA formation low during storage. There was no statistically significant difference in terms of mean MDA content between these two treatments during storage time ($p > 0.05$). Quercetin treatment preserved the integrity of the cell membrane of cut potatoes and extended the shelf life. Liu et al. (2018) showed that treating cut potatoes with 0.1% cod peptides significantly delayed the increase in MDA contents compared to control. Liu et al. (2019) reported that purslane extract significantly delayed the increase of MDA in fresh-cut potato strips.

There was no statistically significant difference between the H_2O_2 contents of the treatment groups at initial and on the first day of storage ($p > 0.05$). It was observed that the H_2O_2 contents of the treatment groups fluctuated in the following days of storage. While the control group had a significantly higher H_2O_2 content on day 6 than the other groups ($p < 0.05$), it had a significantly lower H_2O_2 content on day 8 compared to the others ($p < 0.05$). This situation was caused by the sudden increase in H_2O_2 content of the quercetin and ascorbic acid groups on day 8. In a study, it was reported that the H_2O_2 content of fresh-cut broccoli treated with 100 μM melatonin was 18% lower than the control group after 25 days of storage (Wei et al., 2020).

3.4. Effect of quercetin on phenolic compounds of potatoes

Phenolic compounds play a role in enzymatic browning since they are substrates in the reaction where PPO catalyzes the conversion of o-quinones (Nokthai, Lee, & Shank, 2010). In Fig. 4, the change of some phenolic compounds in potato samples during storage is shown. At the end of storage, 1.21, 1.78, and 2.44 fold increase in amounts of CHA were observed of quercetin, AA and control treatments, respectively. It was observed that the quercetin treatment kept the CHA amount more balanced level during storage. The increase in CHA in the samples can be caused by the production of phenolic compounds as a result of PAL activity and the percentage increase of dry matter as a result of weight loss. It was seen that the amount of CHA showed strong positive correlations with PAL activity and weight loss (Table 1). CHA, the major phenolic compound in potatoes, is one of the important substrates of the enzyme PPO, which causes browning (Cantos et al., 2002). However, one study reported that CHA inhibited PPO (Cheng et al., 2020). In our study, it was seen that there is a positive correlation between CHA and PPO. There was no statistical difference between the CHA amounts of the control and quercetin treatments at the end of storage ($p > 0.05$). However, there was a significant difference between AA and other treatments ($p < 0.05$).

Although there was a fluctuation in the caffeic acid contents of samples during the storage process, it was determined that the amount of caffeic acid decreased in all the treatments at the end of the storage. The highest caffeic acid content, both at the beginning and at the end of storage, was observed in the samples treated with quercetin. Except for the dramatic decrease in Day 3, the caffeic acid content in the AA-treated samples remained in balance. According to the beginning storage value, a 7% loss was observed in the caffeic acid content of the AA treatment, while this loss increased to 37% in quercetin and control samples. Torres, Aguilar-Osorio, Camacho, Basurto, and Navarro-Ocana (2021) reported that PPO showed the lowest affinity for caffeic acid among the caffeoylquinic acid derivatives. In a study conducted on fresh-cut apple slices, it was reported that CA content decreased in the control sample after 15 days of storage and increased in citric acid and UV-treated samples (C. Chen et al., 2016).

Trans-cinnamic acid is the first phenolic compound formed as a result of the conversion of substrate L-phenylalanine in the reaction catalyzed by PAL and it is the first step in phenylpropanoid metabolism (Ge et al., 2021). In the continuation of this pathway, phenolic

Table 1
Pearson correlations of analyzed values of potato samples.

	PPO	PAL	MDA	H_2O_2	CHA	CA	TCA	FA	TPC	AA	WL
PPO	1	0.770**	0.240	0.064	0.447**	-0.215	0.807**	0.255*	0.527**	0.196	0.606**
PAL		1	0.218	0.331**	0.537**	-0.269*	0.836**	0.181	0.568**	0.159	0.632**
MDA			1	0.209	-0.230	0.102	0.184	0.182	-0.020	-0.238	0.124
H_2O_2				1	0.108	0.190	0.220	-0.260*	-0.092	-0.164	0.088
CHA					1	-0.055	0.543**	0.239	0.538**	0.171	0.591**
CA						1	-0.197	-0.090	-0.378**	-0.236	-0.272*
TCA							1	0.209	0.481**	0.210	0.671**
FA								1	0517**	0.180	0.134
TPC									1	0.320*	0.425**
AA										1	0.022
WL											1

PPO: polyphenol oxidase, PAL: phenylalanine ammonia-lyase, MDA: malondialdehyde, H_2O_2: hydrogen peroxide, CHA: chlorogenic acid, CA: caffeic acid, TCA: trans-cinnamic acid, FA: ferulic acid, TPC: total phenolic content, AA: antioxidant activity, WL: weight loss.

* $p < 0.05$.

** $p < 0.01$.

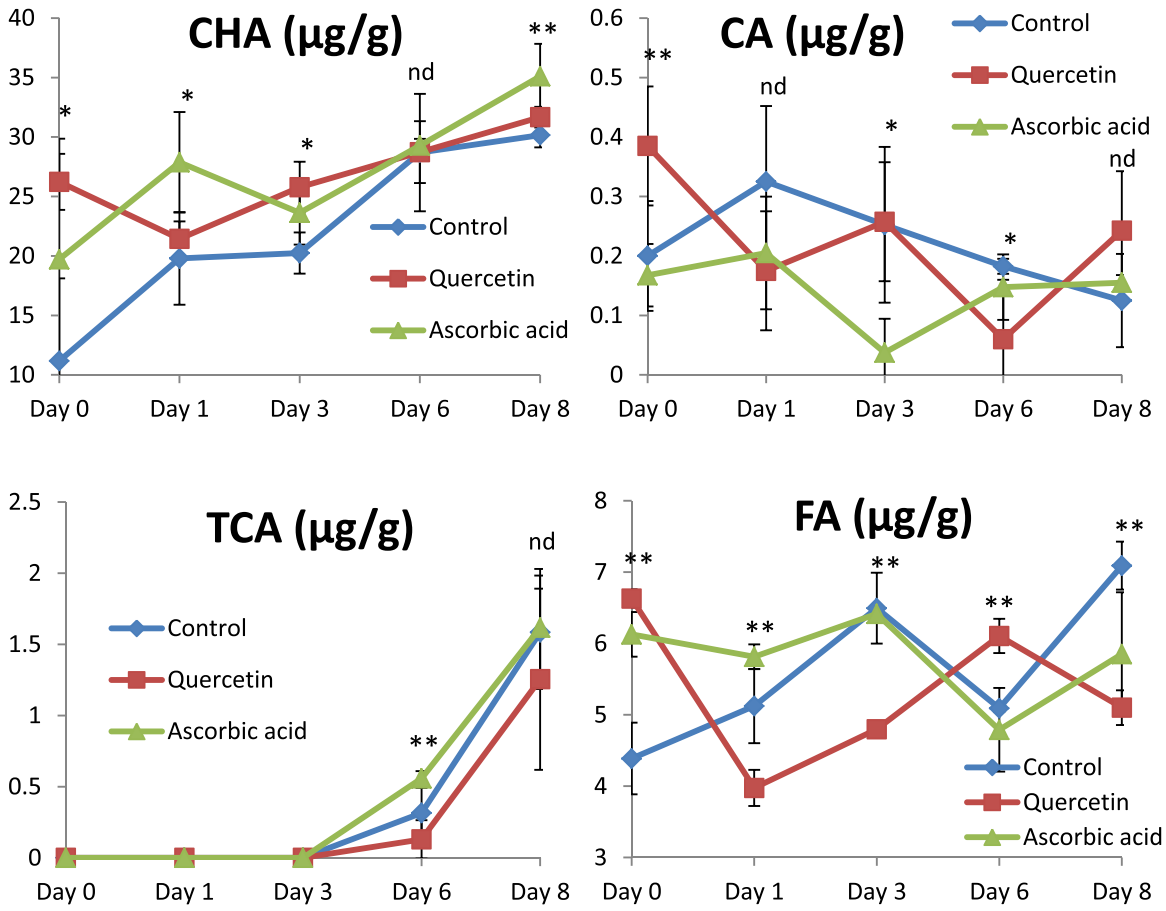

Fig. 4. Effect of quercetin on the phenolic acid content of cut potatoes during storage time. Error bars represent standard deviations. Nd:no difference, * $p < 0.05$, ** $p < 0.01$, CHA: chlorogenic acid, CA: caffeic acid, TCA: trans-cinnamic acid, FA: ferulic acid.

compounds such as chlorogenic acid, protocatechuic acid, caffeic acid and di-caffeoyl tartaric acid are formed (Wang et al., 2015). In this study, it was determined that TCA showed a very strong positive correlation with PAL and PPO and a strong positive correlation with CHA and TPC (Table 1). As seen in Fig. 4, TCA could not be determined in all samples until day 6 of storage. The amount of TCA in the samples treated with quercetin was significantly lower than in the control and AA-treated samples on day 6 ($p < 0.01$). Again, the samples treated with quercetin were seen to have lower TCA content than other treatments at the end of storage. Considering the strong correlation of TCA with PPO that causes browning and with phenolic compounds such as CHA, which are the substrate of this reaction, low amount of TCA kept during storage will extend the shelf life of fresh-cut potatoes. It is important in this respect that the TCA contents of the samples treated with quercetin remain low compared to other treatments.

There was a positive correlation between the amount of ferulic acid and PPO (Table 1). In control, the ferulic acid content increased at the end of storage ($p < 0.01$). This may be since that the weight loss in control is much higher than in other treatments. In the quercetin treatment, the ferulic acid content decreased at the end of storage ($p < 0.01$). Significant reductions were observed in the ferulic acid content of the samples treated with quercetin on day 1 and day 8 and in the ferulic acid content of the control and AA samples on day 6 ($p < 0.05$). These decreases are thought to be due to PPO activity. The ferulic acid average of the quercetin treated samples in storage time was lower than the averages of other treatments. In a study, ferulic acid was detected between 1 and 6 mg/kg DW in different potato cultivars (Albishi et al., 2013).

3.5. *Effect of quercetin on TPC and antioxidant activity of potatoes*

There were strong positive correlations between TPC and PPO, PAL, TCA, CHA, FA (Table 1). With PAL activity, the accumulation of phenolic compounds in potatoes increases and this increase leads to an increase in PPO activity. As can be seen in Fig. 5, TPC in samples treated with quercetin at the end of storage was significantly lower than that of others ($p < 0.05$). In control, TPC increased continuously throughout storage. This increase in TPC is due to the formation of phenolic compounds as a result of the high activity of PAL. As seen in Table 1, a significant positive correlation was found between PAL and TPC. Quercetin and AA treatment kept the TPC content of the samples more balanced, though fluctuating. The TPC of the AA-treated samples remained above 3100 µg/g throughout storage. Samples treated with quercetin did not reach this TPC level during storage. This is because the presence of quercetin prevents the accumulation of phenolic compounds. In a study, fresh-cut potatoes were subjected to *Sonchus oleraceus L.* extract and ultrasound treatments, it was reported that the highest increase in TPC at the end of storage occurred in control (Qiao et al., 2021). In another study, while the TPC of fresh-cut potatoes immersed in water and immersed in different cod peptide solutions increased at the first 6 days of storage, a decrease was observed after 8 days of storage (Liu et al., 2018).

The effect of storage in the control sample on the antioxidant activity value was found to be significant ($p < 0.01$), while the effect of the storage was found to be very significant ($p < 0.001$) in the quercetin and AA treated samples. Antioxidant activity of the control decreased dramatically on the first day of storage and then increased until the end of storage. The antioxidant activity of the samples treated with quercetin

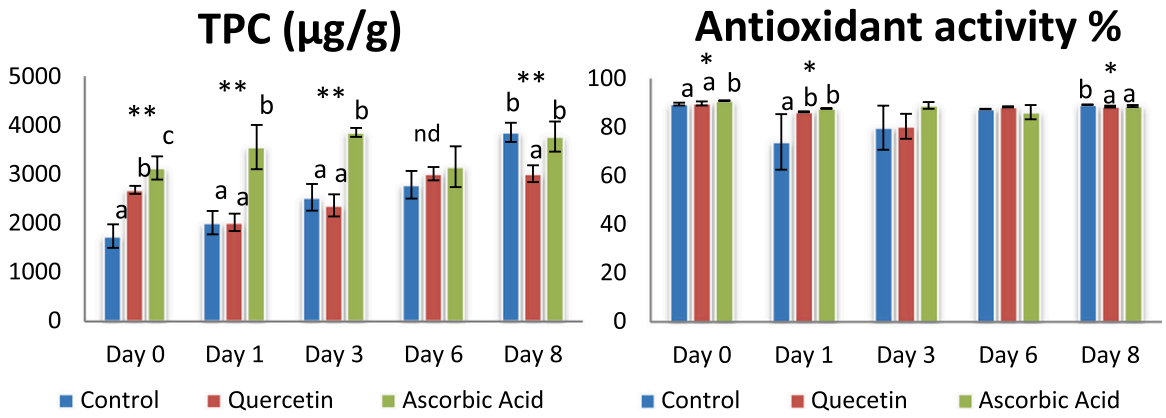

Fig. 5. The effects of quercetin on TPC and antioxidant activity of fresh-cut potatoes during storage time. Different lowercase letters indicate significant differences ($\alpha = 0.05$) according to the Duncan multiple comparison test ($p < 0.05$). Error bars represent standard deviations. Nd:no difference, * $p < 0.05$, ** $p < 0.01$, TPC: total phenolic content.

decreased until day 3. After this point, there was an increase until the end of storage. The antioxidant activity of AA fluctuated during storage. Although there were fluctuations in antioxidant activity during the storage time, there was no significant difference between the antioxidant values at the beginning and end of the storage of each treatment group ($p > 0.05$). At the end of storage, the antioxidant activity of the control was significantly higher than that of other ($p < 0.05$). This is because the highest weight loss is seen in control. As can see in Table 1, there was a positive correlation between antioxidant activity and weight loss. In a study, it was reported that an increase in antioxidant activity was observed in cut potatoes immersed in acid-heat coagulated whey and commercial whey solutions during storage (Palamutoğlu, 2020). In another study, potato slices were subjected to immersion in water at various time intervals (0–30 min), and it was reported that the antioxidant activity of all samples was increased during the storage period (Gong et al., 2019).

3.6. Evaluation of quercetin as an anti-browning agent

PPO catalyzes oxidation reactions that cause browning in fresh-cut products. It has been reported that quercetin competitively inhibits PPO and the inhibition occurs because the pyrone part in the structure of quercetin is formed as a result of chelation of copper in PPO (Chen & Kubo, 2002). The lowest PPO activity and BI value at the end of storage were observed in the samples treated with quercetin. Decreased activity of PPO reduced brown-colored melanin formation and as a result, the browning index remained low.

Quercetin is produced in plants against stress conditions and is responsible for protecting the structure. The production pathway of quercetin and other flavonoids begins with the conversion reaction of phenylalanine to trans-cinnamic acid, catalyzed by the PAL enzyme (Singh et al., 2021). At the end of storage, the lowest PAL activity and TCA amount were seen in the samples treated with quercetin. This indicates that fresh-cut potato samples treated with quercetin are under less stress than that of others. High significant correlations were found between TCA and both PAL and PPO (Table 1). Because the formation of trans-cinnamic acid is also the starting point for the production of other phenolic compounds. Phenolic metabolism has been reported to play an important role in the discoloration of minimally processed potatoes during curing (Sun et al., 2015). Phenolic compounds are the substrate of browning reactions caused by PPO. It has been reported that the enzymatic browning activity is directly proportional to the amount of phenolics in the plants (Selvarajan, Veena, & Manoj Kumar, 2018). There was a positive correlation between PPO and FA, and strong positive correlations between PPO and TCA, CHA and TPC (Table 1).

Stress conditions resulting from cutting potatoes activate phenylpropanoid metabolism. One of the end products of this metabolism is quercetin. The presence of quercetin in the cut potato samples is predicted to cause feedback inhibition on the PAL, one of the regulatory enzymes of the phenylpropanoid metabolic pathway. Indeed, treatment with quercetin kept the CHA content in balance. At the end of storage, the lowest FA, TCA and TPC were found in the samples treated with quercetin. As a result, treatment with quercetin reduces the formation of phenolic compounds, which are substrates of PPO and provides secondary protection by preventing the accumulation of enzymatic browning substrates in the environment.

4. Conclusion

This study showed that 25 mg/100 mL quercetin treatment was effective in controlling browning and maintaining the quality of fresh-cut potatoes. Quercetin treatment kept the PPO and the PAL activity, BI value and MDA content significantly lower. Quercetin treatment decreased PAL activity and reduced TCA formation, preventing the accumulation of phenolic compounds, which are substrates of PPO. The lowest TPC and TCA at the end of storage were seen in the treatment with quercetin. In addition, while the amount of CHA during storage increased 1.21 fold in quercetin treatment, this increase was 1.78 and 2.70 fold in the ascorbic acid and control treatments, respectively. There were strong positive correlations between PPO and PAL, TCA, TPC, CHA. In the light of the data obtained, the quercetin treatment has potential application value in improving the quality and extending the shelf life of fresh-cut potatoes. The use of safe and healthy preservatives such as quercetin in the fresh-cut food industry will increase as people's interest in minimally processed, safe and natural products increase.

Declaration of competing interest

The author declares that he has no conflict of interest.

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