

ORIGINAL ARTICLE

Food Engineering, Materials Science, and Nanotechnology

Prediction model of browning inhibitor concentration and its optimal composition for mass processing of ready-to-eat fresh-cut ‘Fuji’ apple (*Malus domestica* Borkh.) strains

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Funding information

Ministry of Food and Drug Safety of the
Republic of Korea; National Research
Foundation of Korea; Ministry of
Education

Abstract: In this study, we optimized the composition of the browning inhibitor for apples and established a prediction model for the browning inhibitor concentration in mass-processed fresh-cut apples based on electrical conductivity measurements. The “Fuji” apples that were harvested in Chungju, Korea, were used for this study. Vitamin C mixture (VCM) and trehalose (Tre) were used as browning inhibitors at a 4% ratio. The browning reaction under $\Delta 3$ of BI (browning index) for 5 days was defined as the target shelf-life of the apple flesh. The Δ BI of VCM and Tre was lower than that of VCM by 4%. It is revealed that the electrical conductivity of the browning inhibitor was highly correlated with its concentration and the number of soaked apples. Finally, the regression of the conductivity was fitted as $Y = -0.0024 \times (\text{number of soaked apples}) + 0.5111$ ($R^2 = 0.9931$). In the validation test, the conductivity must be maintained at 0.4373 S/m or higher to maintain the target anti-browning level of $\Delta 3$ or less, which corresponded to ~80% of the initial qualitative level after manufacture. The conductivity measurement of the browning inhibitor is suitable for monitoring and predicting its concentration in the mass processing of fresh-cut apple production due to the convenience of this method.

KEYWORDS

browning, electrical conductivity, fresh-cut apple, shelf-life

Practical Application: The conductivity measurement of browning inhibitors can be applied not only to the mass processing of apple production but also to the anti-browning treatment of other fruits and vegetables, due to the convenience of this method. From these research results, it is expected to derive

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a formula that can predict the concentration of browning inhibitors through simple experiments for other fruits or vegetables.

1 | INTRODUCTION

Browning is a major factor in damaging the nutritional and aesthetic qualities of fruits. In particular, the rapid browning reaction of many fruits, such as apples and bananas, has caused severe problems in the processing, and various methods have been used to reduce it and maintain its quality. Control and prevention of enzymatic browning reactions are divided into physical and chemical methods. The physical method includes heat treatment, avoidance of oxygen exposure, use of low temperatures, and irradiation. Heat treatment, such as blanching, can easily inhibit enzyme activity because enzymes constituting proteins are denatured (Moon et al., 2020). For example, enzymatic browning is inhibited by heat treatment at 60°C for 3 min prior to brewing in the wine-making process (Sacchi et al., 2005). However, blanching can impart undesirable color or flavor and destroy the texture, and heating treatment for fruits at high temperatures may alter their taste and smell.

The browning reaction in food is categorized into enzymatic and nonenzymatic ones, both of which contribute to the deterioration of food during storage and processing. Among these, enzymatic browning observed primarily in fruits and vegetables occurs when components of these foods react with oxygen in the air, resulting in a gradual browning effect facilitated by enzymes such as oxidase. When fruits and vegetables suffer damage such as bruising, cutting, peeling, or exposure to certain conditions, they quickly darken due to the oxidation of phenolic compounds, forming brown melanins when exposed to air. Enzymatic browning, catalyzed by polyphenol oxidase (PPO), found in many fruits, vegetables, and certain seafood, is the leading cause of this discoloration (Jiang et al., 2016). Vegetables or fruits such as apples, bananas, lettuce, and potatoes contain substantial amounts of polyphenolic compounds alongside the enzyme PPO. When these fruits or vegetables are peeled or cut, PPO catalyzes the oxidation of polyphenols by atmospheric oxygen, forming quinones and subsequent dark polymerization. The activity of PPO plays a crucial role in regulating enzymatic browning (Friedman, 1996; Moon et al., 2020).

The chemical methods include acidification or reduction with antioxidants, chelating agents, or natural extracts. Reducing agents, sulfates, and their derivatives act as irreversible inhibitors of PPO. Antioxidants such as

ascorbic acid, L-cysteine, and 4-hexylresorcinol can bind to the intermediates and prevent melanin formation (Arias et al., 2007).

Among them, the United States Food and Drug Administration has banned the use of sulfites or sulfur dioxide gas in fruits due to concerns about their harmfulness. However, the controversy surrounding sulfites necessitates the development of new methods for preventing fruit browning. Despite their effectiveness, 4-hexylresorcinol is deemed unsuitable for commercial use in fruits due to its high cost and safety concerns. Similarly, L-cysteine, containing sulfur and emitting a characteristic odor, is considered inappropriate for fruit preservation. While effective in preventing browning initially, ascorbic acid and citric acid suffer from the disadvantage of their effects not being consistently maintained over time (Kang, 2015; Rupasinghe et al., 2005).

Trehalose is one of the widespread carbohydrates in nature and is composed of two glucose molecules linked by an α,α -1,1'-O-glycosidic bond. Trehalose is generally recognized as safe (GRAS) by the US Food and Drug Administration (Mancini et al., 2012). It is primarily known for its ability to protect proteins or other biomolecules under stress conditions such as very high or low temperature, dehydration, and osmotic stress (Iordachescu & Imai, 2008). Unlike sucrose, trehalose exhibits resistance to non-enzymatic browning primarily because of the Maillard reaction and caramelization (Iturriaga et al., 2009). However, Aktas et al. (2013) reported that trehalose is also effective against enzymatic browning, as it interacts with PPO, a key enzyme involved in this process. Meanwhile, ascorbic acid (vitamin C) is similar in structure to glucose. Vitamin C is a water-soluble, odorless, white, crystalline compound insoluble in fat and is a representative antioxidant (Nishikimi et al., 1994). In general, PPO involved in browning is known to have optimal activity at pH 5.0–7.0 and to be inhibited at pH 3.0 or lower (Zemel et al., 1990). Therefore, vitamin C can inactivate PPO by lowering the pH, and it is known to bind to the intermediate due to its antioxidant action and plays a role in preventing melanin formation (Arias et al., 2007).

In our previous study (Lee et al., 2022), we tested a mixture of a commercial browning inhibitor, vitamin C mixture (VCM), and rice bran extract. This combination could serve as a promising alternative anti-browning agent. However, we needed more information regarding a concentration prediction model for the mass processing

fresh-cut apples. To enable continuous and mass processing, it is crucial to determine the optimal concentration of the browning inhibitor and develop a prediction model to monitor its concentration. While there are studies on the kinetics of activity reduction over storage periods, such as a vitamin C reduction model, there currently needs to be research on a process applicable in industrial settings. Therefore, this study aims to develop a concentration prediction model tailored for mass processing fresh-cut apples.

2 | MATERIALS AND METHODS

2.1 | Apple flesh samples preparation and treatment

One of the common varieties of apples, Fuji was selected for this study. The apples were obtained grocery market in Chungju, Korea, and purchased from the market. Among them, the apples with a good appearance and weight between 200 and 250 g were selected, cleaned with tap water for 1 min, and then the residual moisture was removed. The apples were cut into 1.8 cm³. After 10 s, the samples were soaked in a browning inhibitor solution for 1 min.

The browning inhibitor used in this study was a VCM, which is a mixture of vitamin C and its derivatives (VCM; Food Freshly AFC GmbH) and food-grade trehalose (Tre) from Hayashibara Co., Ltd. at a 4% ratio. The apples treated with browning inhibitor were dried at a wind speed 3.5 m/s for 40 s and stored at refrigerated condition (4°C). The goal of its target shelf-life was set up for 5 days, and browning index (BI) was measured for 7 days considering the safety factor. In addition, the quality change limit of apple color was set to Δ3 based on a preliminary study.

2.2 | Color and browning index

The color was analyzed using a colorimeter (CR400; Konica Minolta Co., Ltd.) that calibrated with the standard white plate ($Y = 94.2$, $x = 0.3167$, $y = 0.3336$). Every cut surface of the apple cubes was measured six times each, and a total of four times were repeated, and the average values were expressed as L , a^* , and b^* values, respectively, and used as the color values of the apple cubes. The BI was calculated using Equation (1) (Shimizu et al., 2021):

$$BI = \frac{100(x - 0.31)}{0.17}, \quad (1)$$

where x was computed according to Equation (2):

$$x = \frac{a^* + 1.75 L}{5.645 L + a^* - 3.012 b^*}. \quad (2)$$

The ΔBI was calculated as follows:

$$\Delta BI = BI_t - BI_0, \quad (3)$$

where BI_t means the BI at the time and BI_0 represents BI at the initial.

2.3 | Electrical conductivity

The electrical conductivity of the anti-browning solution was measured with a conductivity meter (CM-31P; DKK-TOA Corp.). After setting the instrument to the automatic temperature compensation mode, combine the electrode and immerse it in a standard calibration solution. After dipping the electrode in the sample to be measured and at a certain time, the value displayed on the device was set as conductivity when it was stabilized.

2.4 | Sensory evaluation

The sensory evaluation was conducted to determine the effects of the browning inhibitors on the sensory properties of the flesh samples treated with the browning inhibitor. The apple samples were divided into three groups: those treated with distilled water (D.W.), VCM 4%, and VCM 2% + Tre 2%. The panelists were associated with 36 people who have no objection to apples. The samples were put in a container with a lid and used for evaluation after 1 day of storage at refrigerated condition. The evaluation items were color, taste, flavor, mouthfeel, and overall acceptability, and a nine-point-scale method was used for the evaluation (1: very weak, 5: moderate, and 9: very strong). The study was reviewed and approved by the Korea University IRB, and informed consent was obtained from each subject prior to their participation in the study (IRB approval No. KUIRB-2023-0391-01).

2.5 | Statistical analysis

Statistical analysis of the data obtained from each experiment involved the analysis of variance and Duncan's multiple range test by SAS 9.3 (SAS Institute Inc.) to analyze the significance of differences among the treatments.

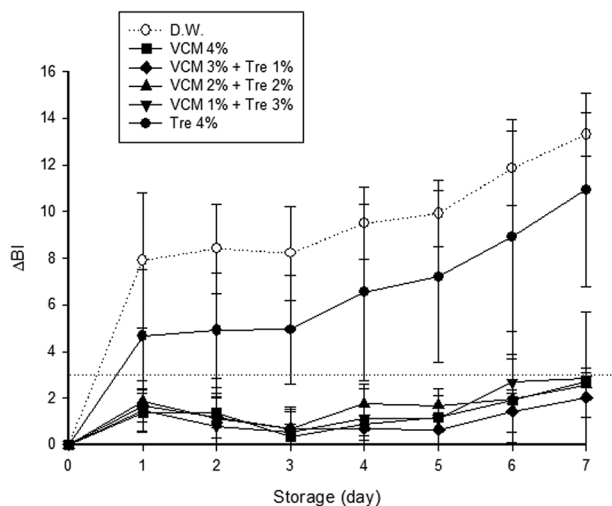


FIGURE 1 Changes in the browning index (BI) of apple flesh cut treated with vitamin C mixture (VCM), trehalose (Tre), mixture of VCM and Tre (VCM + Tre), and distilled water (D.W.) for 7 days. The measurement was performed with triplication.

The data were expressed as the mean $\pm$ standard deviation, and the statistical significance was defined at the 5% level. Correlation analysis was performed with the Spearman's and Pearson's correlation using the R statistics software (ver. 4.30; R Foundation for Statistical Computing). Both correlation coefficients are standardized to fall within the range of -1 to $+1$. A value of 0 suggests no linear or monotonic correlation. As the relationship strengthens, the coefficient approaches either a straight line (Pearson's correlation) or a continuously increasing or decreasing curve (Spearman's correlation), nearing an absolute value of 1 (Schober et al., 2018).

3 | RESULTS AND DISCUSSION

3.1 | Effect of browning inhibition by mixing ratio of VCM and Tre

Figure 1 shows changes in the BI of the apple flesh samples treated with VCM and Tre for 7-day storage. The BIs of all groups increased during storage. Especially the Tre 4% group showed higher BI than others. The VCM 4%, VCM 3% + 1% Tre, VCM 2% + Tre 2%, and VCM 1% + Tre 3% groups inhibited the browning reaction under $\Delta 3$ during 5-day storage, which was defined as the target shelf-life. Finally, the ΔBI of VCM 4%, VCM 3% + Tre 1%, VCM 2% + Tre 2%, and VCM 1% + Tre 3% was 2.68 ± 1.42 , 2.03 ± 0.42 , 2.57 ± 0.26 , and 2.85 ± 1.42 , respectively. A low concentration of VCM and a high concentration of Tre can provide

economic benefits. However, VCM 1% + Tre 3% reached almost $\Delta 3$, the quantitative goal of this study. Thus, the final composition of the inhibitor was determined to be the composition of VCM 2% + Tre 2%.

According to Grimm et al. (2012), the treatment of 0.3 mM ascorbic acid for 10 min at room temperature decreased the browning reaction of apples, and Du et al. (2012) reported that 0.08% phytic acid was effective to reduce PPO generation by $\sim 99.2\%$. Similarly, Martínez-Hernández et al. (2019) studied the anti-browning effect of L-ascorbic acid for fresh-cut apples made with Braeburn cultivar. In the study, the BI decreased when the apples were dipped into 10 g/L ascorbic for 8 min. Similar to these reports, it is also confirmed that the BI decreased in this study.

3.2 | Sensory evaluation of browning inhibitor-treated apple sample

As shown in Table 1, VCM 2% + Tre 2% group did not show a significant difference compared with the groups of D.W. and VCM 4% treatment in taste and flavor. The VCM 2% + Tre 2% treatment group did not show significance compared to the D.W.-treated group as a control, and it was suggested that the VCM 2%+Tre 2% combination did not affect taste and flavor. Furthermore, the group treated with the combination was superior to the control in color, mouthfeel, and overall acceptability. Consequently, it is considered that the combination of VCM 2% + Tre 2% did not affect sensory properties, and this combination is valuable as a browning inhibitor that can improve the palatability of sliced apples.

From this result, the anti-browning treatment for apples was found to effectively maintain its sensory properties, such as firmness, color, taste, and so on. According to Utama et al. (2021), the anti-browning treatments for apples including dipping in solution of ascorbic acid, citric acid, sodium metabisulfite, or L-arginine were useful to maintain its firmness during storage. In addition, Albanese et al. (2007) reported that trehalose-treated apples showed porosity decrease, and the trehalose-treated samples showed superior firmness to untreated ones during storage. According to them, it is due to the properties of trehalose, which has an ability to bond onto the surface of molecular structures by hydrogen bond. Kopjar et al. (2016) reported that the group that added trehalose when making orange jelly showed higher antioxidant activity than those that did not. They noted that this effect occurred due to the interaction between trehalose and pectin. This is presumed because trehalose forms a stable intramolecular

TABLE 1 Sensory evaluation of apple flesh samples treated with distilled water (D.W.), vitamin C mixture 4%, and vitamin C mixture 2% + trehalose 2%.

	Color	Mouthfeel	Taste	Flavor	Overall acceptability
D.W.	4.89 ± 0.35b	6.22 ± 0.28b	5.44 ± 0.31a	5.89 ± 0.35a	5.58 ± 0.29b
VCM 4%	7.00 ± 0.22a	6.83 ± 0.21ab	5.69 ± 0.35a	5.92 ± 0.31a	6.28 ± 0.25ab
VCM 2% + Tre 2%	7.17 ± 0.26a	7.00 ± 0.25a	6.06 ± 0.33a	6.00 ± 0.32a	6.67 ± 0.26a

Note: Different lowercase letters indicate statistically significant differences between the groups ($p \leq 0.05$).

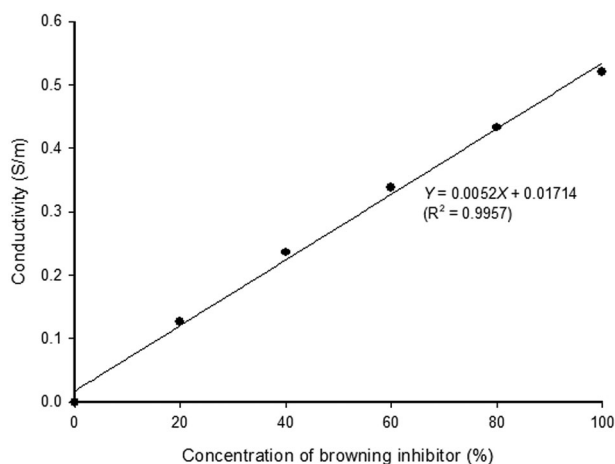


FIGURE 2 Standard curve of electrical conductivity according to the concentration of the optimized browning inhibitor for apple.

complex with an unsaturated compound with a cis-type olefin double bond (Oku et al., 2003, 2005).

3.3 | Changes in electrical conductivity

3.3.1 | Correlation between browning inhibitor and electrical conductivity

The browning inhibitor (VCM 2% + Tre 2%) was diluted to 80%, 60%, 40%, and 20% using D.W., and the change in electrical conductivity according to the concentration of the browning inhibitor is shown in Figure 2. It is revealed that the browning inhibitor concentration increase caused an increase in electrical conductivity. The regression for the concentration was $Y = 0.0052X + 0.0171$ ($R^2 = 0.9957$). Consequently, the concentration of the browning inhibitor could be estimated by this regression. The electrical conductivity is defined as the ability of a substance to conduct an electric current. It is widely applied to a qualitative parameter for water (Marandi et al., 2013), or quality control in chemical analyses (Marandi et al., 2013; Vila et al., 2005). From this result, it is expected that the concentration of the browning inhibitor can be checked and controlled in real time since the measurement of electri-

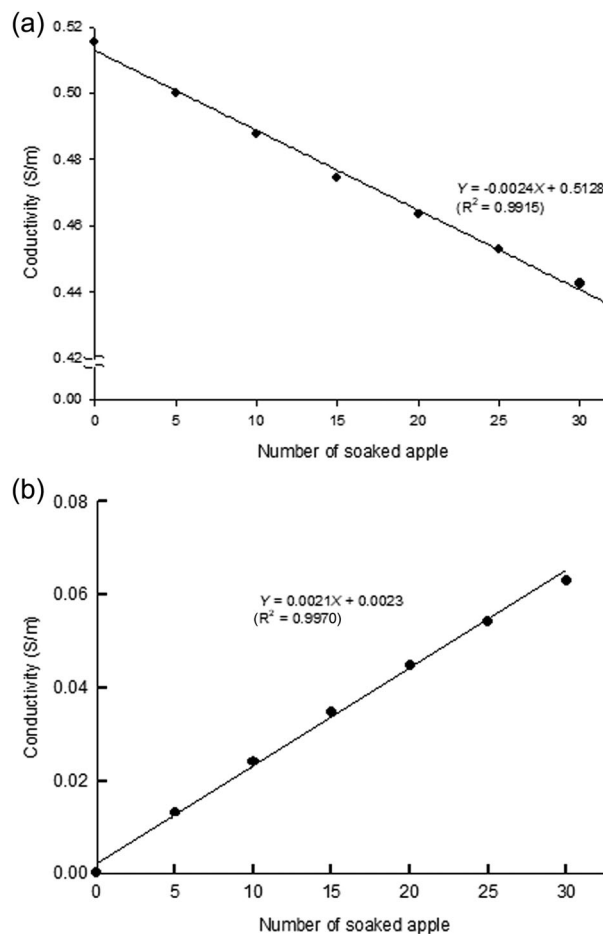


FIGURE 3 Changes in electrical conductivity of the browning inhibitor (a) and D.W. (b) according to soaking apple.

cal conductivity can be easily applied in the fresh-cut apple process.

3.3.2 | Changes in electrical conductivity by soaking apple

One apple was sliced into eight pieces of the same size and soaked in a browning inhibitor or D.W. for 1 min, and the electrical conductivity of the soaking solution was measured for each five-apple treatment. As shown in Figure 3a, the electrical conductivity of the inhibitor

agent tended to decrease as the number of processing sliced apples increased. This is presumed to be due to material transfer between the apple and the browning inhibitor during the processing of the sliced apple. In particular, it is believed that this is due to the fact that the vitamin C in the browning inhibitor decreased because of repeated soaking treatment. Figure 3b is the result of the analysis of the electrical conductivity for every five apples while soaking the sliced apple in D.W. for 1 min. As the treatment was repeated, the electrical conductivity of D.W. increased from 0.00 to ~ 0.06 S/m at the 30th treatment. This is thought to be due to the elution of specific components from the apple during the processing of apples. However, this suggests that the decrease of the conductivity caused by the components of the browning inhibitor transferring to the sliced apples was greater than the increase of the electrical conductivity by elution of specific elements from the apples to the inhibitor. The electrical conductivity by changes in components of browning inhibitor in the sliced apple treatment could be calculated by the difference from slopes and intercepts of Figure 3a,b. Finally, the regression of the conductivity was $Y = -0.0024 \times (\text{number of soaked apples}) + 0.5111$ ($R^2 = 0.9913$, Equation 4).

3.3.3 | Regression fitting for the concentration of browning inhibitor

To measure the electrical conductivity of the anti-browning agent according to the number of times the apple slices were immersed, the first, 21st, and 31st soaked apples were stored for 7 days, and the browning was measured. The first, 21st, and 31st soaked apples were dehydrated for 40 s, put in a plastic container, and kept refrigerated. Subsequently, the color change was observed for 7 days (Figure 4). On the first day of the experiment, the ΔBI of the first, 21st, and 31st immersed apple samples was 1.77 ± 0.90 , 1.33 ± 0.61 , and 4.48 ± 1.02 , respectively, and the 31st soaked sample was browned beyond the quality limit of $\Delta 3$, browning proceeded the fastest during the entire experimental period. On the other hand, ΔBI on the fifth and seventh days of the first and 21st immersed apples in the browning inhibitor was 1.61 ± 0.75 , 1.80 ± 0.86 , and 2.13 ± 0.87 , 3.44 ± 1.32 , respectively. On the fifth day set as the expiration date, it was observed that both samples were browned within the quality limit without significance ($p > 0.05$). However, on the seventh day, the safety factor was applied, the ΔBI of the 21st soaked sample exceeded the quality limit, and there was no significant difference ($p > 0.05$).

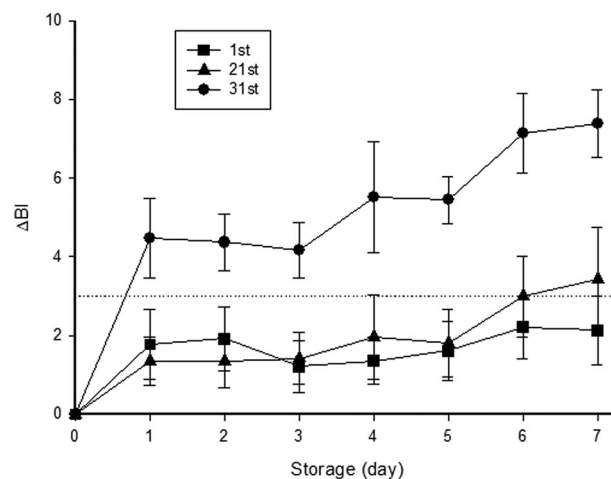


FIGURE 4 Changes in the ΔBI of the apples soaked at the browning inhibitor during the storage period according to the number of soaking times. The treatment was performed with three replications.

3.3.4 | Prediction model inducement

As shown in Table 2, as the soaking treatment was repeated, the regression from the results in Figure 4 tended to fit (R^2 increase), and the electrical conductivity tended to decrease. ΔBI showed a log function form over time, and through these, the log function trend line of ΔBI obtained from apples dipped in the browning inhibitor for first, 21st, and 31st, respectively, as shown in Figure 5. The slope of the regression obtained through the trend line was defined as the E_A , assuming that this represents the efficacy of inhibition. In addition, the relationship between the two variables can be expressed as follows by setting theoretical electrical conductivity (TEC) as the theoretical electrical conductivity that decreases due to the elution of apple components when apples are repeatedly soaked (Table 3). The regression model, $E_A = 0.0324 \text{TEC}^{-4.637}$ ($R^2 = 0.9980$, Equation 5), showed the highest R^2 value, and it is selected as the model that explain well the E_A . To verify this, we measured the L -value at regular intervals from the initial to the 30th apple soaking, and the results shown in Figure 6 were obtained, confirming that this regression model was well fitted. The results of the Spearman correlation analysis of these results are shown in Table 4. The Spearman's and Pearson's correlation coefficients of Table 4 were approximately -0.964 and -0.938 , respectively, indicating Equation (5) was more suitable by fitting with a curvilinear regression model. In the Spearman's correlation, the closer the absolute value of the correlation coefficient is to 1, the closer the regression equation is to

TABLE 2 Regressions from the Δ BI of the apple during the storage period according to the number of soaking times, E_A , and theoretical electrical conductivity (TEC) value.

Number of apples soaked	Regression ^a (X: storage period (day); Y: Δ BI)	E_A ^b	TEC ^c
1	Y = 0.7542 lnX + 0.5262 ($R^2 = 0.67$)	0.7542	0.5111
21	Y = 1.7677 lnX - 0.3904 ($R^2 = 0.86$)	1.7677	0.4211
31	Y = 3.1820 lnX + 0.6578 ($R^2 = 0.92$)	3.1820	0.3761

^aRegression from the Δ BI of the apple soaked at the browning inhibitor during storage.

^bSlop of the regression as an activation energy from the Δ BI of the apple soaked at the browning inhibitor during storage.

^cTheoretical electrical conductivity.

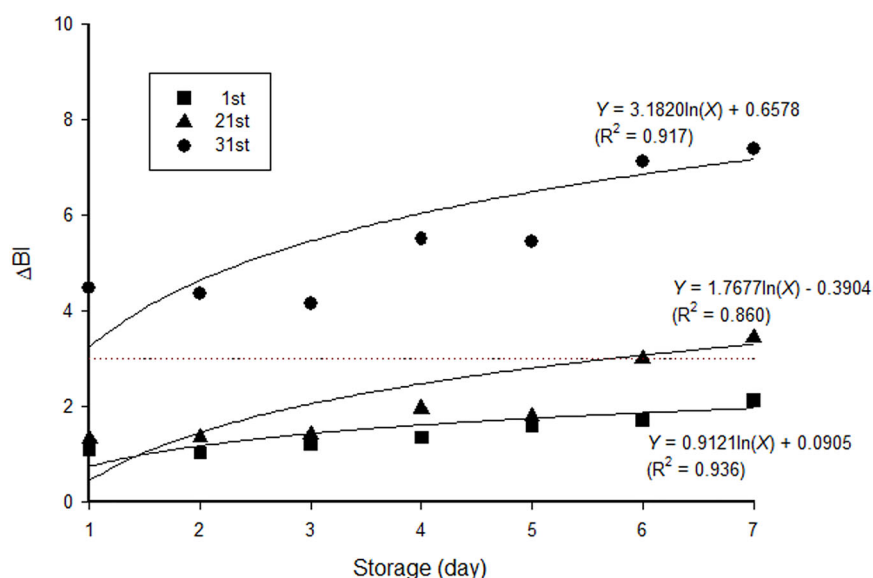


FIGURE 5 Regressions for the Δ BI of the apples soaked at the browning inhibitor during the storage period according to the number of soaking times. X means the storage period (day), and Y represents Δ BI.

TABLE 3 Applicable regression models and R^2 values from theoretical electrical conductivity (TEC)^a and E_A .

Model	R^2
$E_A = 0.0324 \text{TEC}^{-4.637}$	0.9980
$E_A = -7.586 \ln(\text{TEC}) - 4.4962$	0.9409
$E_A = 153.44e^{-10.49\text{TEC}}$	0.9928

^aSlop of the regression as an activation energy from the Δ BI of the apple soaked at the browning inhibitor during storage.

^bTheoretical electrical conductivity.

assumed that there was a constant relationship between Δ BI, target shelf-life (D), and E_A , and this was expressed as follows:

$$\Delta \text{BI} = E_A \times \ln D, \quad (6)$$

where D is the date that has elapsed from the time of treatment with the browning inhibitor. Substituting the relational expression of E_A and TEC obtained above into Equation (6):

$$\Delta \text{BI} = 0.0324 \text{TEC}^{-4.637} \times \ln D. \quad (7)$$

By rearranging Equation (7) for TEC,

$$\text{TEC} = \frac{\sqrt[4.637]{0.0324 \times \ln D}}{\Delta \text{BI}}. \quad (8)$$

the curvilinear (Armstrong, 2019; Schober et al., 2018).

$$E_A = 0.0324 \text{TEC}^{-4.637} \quad (R^2 = 0.9980). \quad (5)$$

Equation (5) was set as the relational expression between the browning inhibitor (VCM 2% + Tre 2%) and E_A . It was

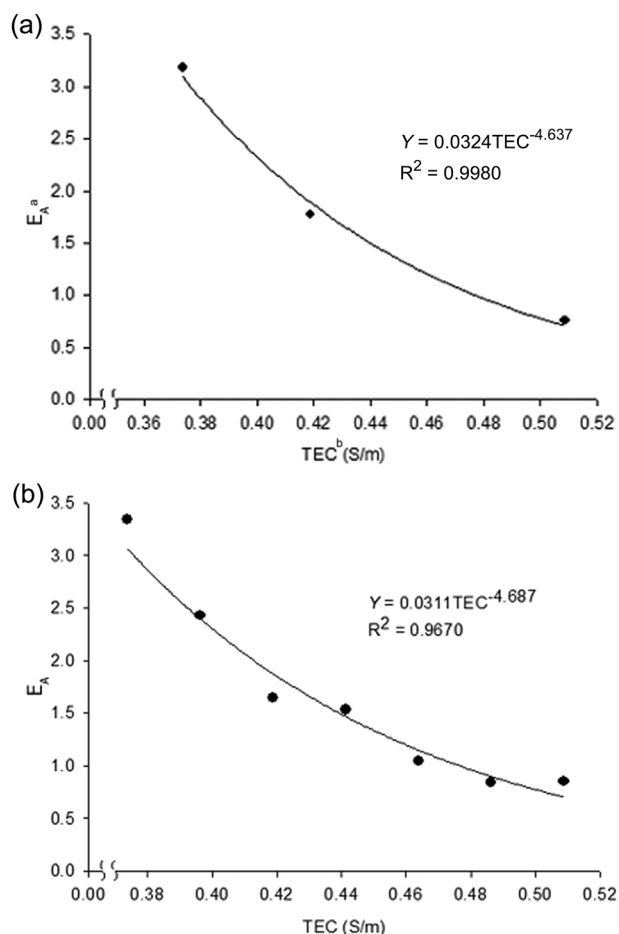


FIGURE 6 Relationship between theoretical electrical conductivity (TEC) and E_A . ^aSlop of the regression as an activation energy from the Δ BI of the apple soaked at the browning inhibitor during storage. ^bTheoretical electrical conductivity.

If the target shelf-life and Δ BI are determined from the induced regression, an operator could assess the conductivity of the required browning inhibitor concentration in the apple soaking process. In addition, this regression model was fitted for the “Fuji” apples soaking process, depending on the types of fruits or the composition of the browning inhibitor. Thus, it is considered that regression for other fruits could be fitted from its EA and TEC values using the same calculation process as above. According to these results, a formula could be derived to predict the concentration of browning inhibitor through simple experiments for any fruit or vegetable. If this formula is implemented, it could automatically adjust the concentration of the browning inhibitor during the mass production of fresh-cut apples. In addition, the electrical conductivity 0.032 method could be used to measure the concentration of various functional substances dissolved in water and ionized, not just vitamin C.

Meanwhile, we calculated the correlation between the storage period and Δ BI using Equation (7) and the TEC

TABLE 4 Validation of the relationship between TEC and E_A and the Spearman's and Pearson's correlation.

Immersed apple	TEC ^a	E_A ^b	Correlation coefficient	
			Spearman's	Pearson's
0	0.5088	0.7542	−0.9643	−0.9381
5	0.4863	0.9170		
10	0.4638	1.1423		
15	0.4413	1.4380		
20	0.4188	1.7677		
25	0.3963	2.3680		
30	0.3738	3.1820		

^aSlop of the regression as an activation energy from the Δ BI of the apple soaked at the browning inhibitor during storage.

^bTheoretical electrical conductivity.

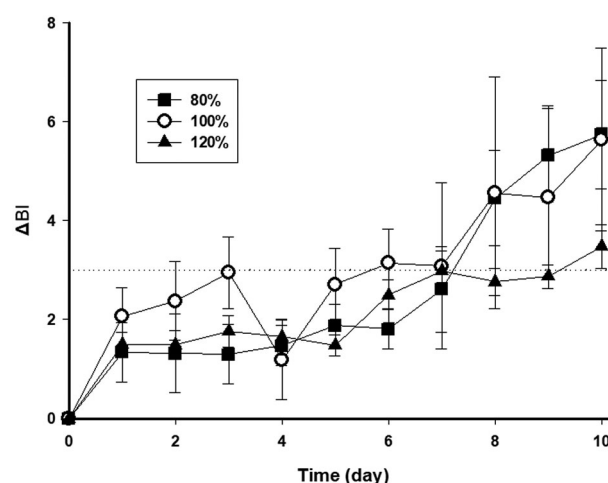


FIGURE 7 Decision of the optimal browning inhibitor concentration by Δ BI and validation of the regression by the electrical concentration. Values are the mean $\pm$ SD ($n = 6$).

and E_A values of the first apple soaking in Table 2 and analyzed the correlation between the storage period and Δ BI. According to this result, the Δ BI is predicted to be ~ 1.4497 on the seventh day of storage after the anti-browning treatment of apples for the first time. In addition, the ability of the anti-browning agent decreased with the repeated soaking process, and the browning prevention effect was significantly reduced in the 31st processed apple, which was predicted to exceed the quality limit of $\Delta 3$ only 1 day after immersion. In this way, the change in Δ BI can be predicted during the storage period after the initial immersion of the apples in the anti-browning agent. In addition, this equation will change depending on the type of anti-browning agent and the type of fruit or vegetable to be treated, and the above equation can be derived and applied by several simple experiments, including measurement of the electrical conductivity of the anti-browning agent and the Δ BI. Therefore, it is applied to predict simply

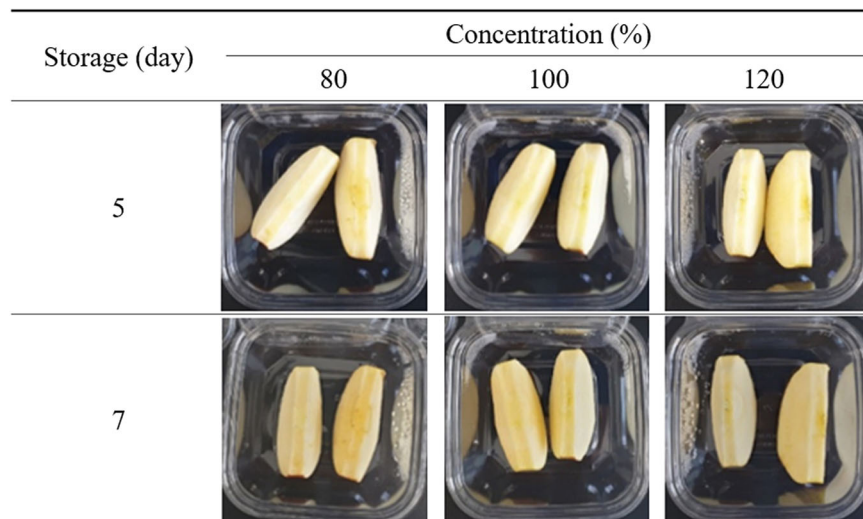


FIGURE 8 Changes in color of fresh-cut apples treated with browning inhibitors with various concentrations for 5 and 7 days.

the browning inhibitor concentration and shelf-life of the anti-browning-treated agricultural products, such as other fruits and vegetables, through some experiments and analysis, including measuring the conductivity of the browning inhibitor at initial and after soaking treatment and fitting a regression from the results.

3.3.5 | Validation test and optimal dosage of the browning inhibitor

Figure 7 shows the ΔBI of the optimized browning inhibitor-treated apples with various concentrations to optimize its dosage in the process. According to the induced regression (Equation 8), it needs to confirm the upper limit of the browning inhibitor in the process through the electrical conductivity. Generally, the shelf-life of fresh-cut apples is 5 days, and the browning inhibitor should control the browning reaction for ~7 days, considering the safety coefficient. Based on the target anti-browning level of $\Delta 3$ or less, to inhibit browning for 7 days using the 2% VCM + 2% Tre solution, the electrical conductivity of the browning inhibitor must be maintained at 0.4348 S/m or higher, and this corresponds to ~80% of the initial quality level of manufacture. Therefore, by setting the minimum concentration required for quality maintenance to 80 and the maximum concentration to 120%, the ability to control the browning reaction for each concentration was confirmed by ΔBI . At the 80% concentration, the ΔBI was found to be 2.61 ± 0.87 and 4.46 ± 0.97 on the seventh and eighth days, respectively, and maintained below $\Delta 3$ until the seventh day but increased rapidly from the eighth day. On the other hand, in the case of the 120%, ΔBI was 2.98 ± 0.39 on the seventh storage day, which was slightly higher than that of the 80% concentration, but after that, the browning was effectively controlled compared to

the other groups. As a result of the actual electrical conductivity analysis of the 80% and 120% concentrations, they were 0.4351 and 0.4431 S/m, respectively. It was similar to the electrical conductivity predicted using Equation (8) (data not shown). Consequently, in fresh-cut apple manufacturing, if the electrical conductivity of the browning inhibitor is maintained at a minimum of 0.4235 to a maximum of 0.4432 S/m, the browning of the apples can be controlled stably for up to 7 days.

Figure 8 shows changes in color of the fresh-cut apples treated with the browning inhibitors with various concentrations. Overall, the higher the concentration of the browning inhibitor, the weaker the degree of browning was observed, and it was found that browning progressed more on the seventh storage day than on the fifth day of storage. In the 120% of the inhibitor-treated group, it can be seen that browning progressed the least between the fifth and seventh days of storage, and it can be seen that the treatment with the 120% concentration is suitable.

4 | CONCLUSION

The use of the composition of VCM and trehalose improved the browning inhibition efficiency. It was revealed that the composition of VCM 2% + Tre 2% was effective. Through this study, it was possible to establish a browning prediction model for Fuji apples and a method for managing the concentration of browning inhibitors in the fresh-cut apple process by measuring the electrical conductivity. The relationship between electric conductivity and solution concentration can be applied to various functional substances easily ionized in water. When modeling the target fruit by referring to this experiment, its concentration will be able to be easily predicted. This method of predicting concentration can be used not

only for vitamin C but also for other substances. Furthermore, it is considered that the application of this method can be used in food regulation science, especially in the standardization and guide for regulation.

Moreover, the potential of this method goes beyond just regulating food quality. It is expected to significantly contribute to the operation of smart factories and processes, as it can be applied not only to apples but also to other vegetables and fruits such as pears and peaches. Based on the results of this study, the concentration of necessary antioxidants can be predicted efficiently according to the distribution environment or timing. This can simplify the prediction of antioxidant concentrations in mass production processes, increase the convenience of the operator, and promote the pursuit of smart factories.

In conclusion, the relationship between electrical conductivity and solution concentration is believed to revolutionize food regulation science and beyond. Its application can lead to better quality control and standardization in food processing and improved efficiency and convenience in mass production processes. It can also pave the way for the realization of smart factories and processes, which will contribute to the development of the food industry.

AUTHOR CONTRIBUTIONS

Soo Min Baek: Methodology; software; formal analysis; data curation. **Sung-Il Ahn:** Writing—original draft; validation. **Sang Hoon Lee:** Writing—review and editing. **Jae-Mun Choi:** Data curation; validation. **Jiyoun Hong:** Data curation; validation. **Young Jun Kim:** Resources; validation. **Bok Kyung Han:** Conceptualization; supervision.

ACKNOWLEDGMENTS

This research was supported by the BK21 FOUR (Fostering Outstanding Universities for Research), funded by the Ministry of Education (MOE, Korea) and National Research Foundation of Korea (NRF), and the grant (Graduate School Education Program of Regulatory Sciences for Functional Food, 21153MFDS604) from the Ministry of Food and Drug Safety of the Republic of Korea.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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How to cite this article: Baek, S. M., Ahn, S.-I., Lee, S. H., Choi, J.-M., Hong, J., Kim, Y. J., & Han, B. K. (2024). Prediction model of browning inhibitor concentration and its optimal composition for mass processing of ready-to-eat fresh-cut ‘Fuji’ apple (*Malus domestica* Borkh.) strains. *Journal of Food Science*, 89, 4986–4996. <https://doi.org/10.1111/1750-3841.17217>