



Article

Evaluation of Different Anti-Browning Treatments on the Quality of Four Colombian Potato Varieties

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Abstract: The increasing demand for fresh and convenient foods has led to the production of Minimally Processed Products (MPPs), which are suitable for culinary and industrial uses. However, cutting potatoes can trigger browning, negatively impacting their sensory and nutritional quality. This study aimed to evaluate different anti-browning methods on Colombian potato varieties (Diacol Capiro, Pastusa, Nevada, and Sabanera) as raw materials for the development of MPPs. The physicochemical properties evaluated included moisture, pH, acidity, enzymatic activity, total phenolic content, vitamin C, and browning index. The anti-browning treatments involved immersing the potatoes in citric acid, ascorbic acid, and garlic extract. Evaluations were carried out over a 15-day storage period in refrigerated conditions. The results indicated that the Sabanera variety had the highest browning index, followed by Nevada, while Diacol Capiro and Pastusa showed lower browning indices, even without the use of technological coadjuvants. Among the treatments, citric acid proved to be the most effective across all varieties, with Diacol Capiro exhibiting the least browning after 15 days. Garlic extract was the least effective against browning. The sensory analysis indicated that an acidic descriptor was noted for both treated (with citric acid) and untreated (control) Diacol Capiro potatoes at similar intensities, suggesting that citric acid did not negatively affect the sensory quality and/or was masked during cooking, enhancing overall quality. In conclusion, the Diacol Capiro variety treated with 1% citric acid is the most appropriate choice for use as a raw material for MPPs without compromising sensory quality.



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1. Introduction

Changes in the lifestyles of the population and the way people eat have generated greater demand for specific types of products. This has led to a trend toward a more practical and healthy diet, in which Minimally Processed Products (MPPs) are viewed as a viable alternative. This transformation represents a significant challenge for the food industry. Minimally Processed Products (MPPs), also known as fourth-range products, are those that have undergone minimal processing for their preparation, e.g., in terms of washing, disinfection, peeling, cutting, and packaging. In recent years, the demand for fresh-cut fruits and vegetables has surged rapidly because of their convenience and practicality, making them an appealing choice for busy consumers [1]. Based on the information provided by the market intelligence firm Mordor Intelligence, the global Minimally Processed Products market is projected to register an annual growth rate of 5.65% during the period from 2023 to 2029. In addition, according to the new research report from Global Market Insights, the market for processed fruits and vegetables, including ready-to-eat salads, is expected to exceed USD 392 billion by 2025 [2].

A promising product for the production of Minimally Processed Products (MPP) is the potato, as it is the most consumed non-cereal food worldwide, representing a sig-

nificant portion of the family basket in many countries due to its high energy contribution to the human diet [3]. The potatoes of the Solanaceae family, *Solanum* genus, and *tuberosum* species are the most cultivated species [4], with high nutritional value and the presence of key compounds such as antioxidants, minerals, and vitamins [5]. According to the Food and Agriculture Organization (FAO), approximately 374 million tons are produced annually. In South America, Colombia ranks third in potato production with 2,526,330 tons, after Peru and Brazil. Although there are over 800 varieties of potatoes in Colombia, only about 13 of them have commercial importance, including Parda Pastusa, ICA-Puracé, ICA-Única, Betina, Diacol Capiro, Tuquerreña or Sabanera, Pastusa Suprema, Pastusa Superior, ICA-Nevada, and criolla Colombia (*Solanum phureja*) potatoes.

On the other hand, fresh-cut vegetables (peeled, sliced, or diced and packaged) are viewed as a commercially viable option in the fresh-cut market, serving as an alternative to pre-cooked or frozen varieties. Consequently, potatoes represent a promising raw material for the development of Minimally Processed Products. However, visual appeal, a determinant quality index for consumer acceptance, is one of the main concerns, as once potatoes are cut they are exposed to enzymatic browning [6]. Chemically, this involves the conversion of phenolic compounds into o-quinones through oxidation by exposure to the air after cutting and slicing because of the interaction between phenolic compounds, oxygen, and enzymes such as polyphenol oxidase (PPO) and peroxidase (POD) [7,8]. This process can catalyze two distinct types of reactions. First, the hydroxylation of monophenols, resulting in the formation of diphenols, and, second, the oxidation of diphenols, leading to the production of quinones [6]. These browning reactions not only diminish their visual appeal, but also cause nutrient loss and affect flavor, resulting in lower consumer acceptance [7].

To inhibit or mitigate this occurrence, several chemical treatments, including reducing agents and chelating compounds, have been used as food additives [9]. In general, PPO can be inhibited in several ways: by acting as chelators and binding Cu^{2+} , by acting as acidulants and lowering the pH, or by acting as a competitive inhibitor [3,10]. Sulfites are recognized as effective reducing agents but their application has been limited due to potential negative impacts on human health [11,12]. Ascorbic acid and citric acid are widely used because they are GRAS (Generally Recognized as Safe) [10].

Natural extracts can also be used to address the browning of fruits and vegetables as GRAS additives [13]. In this regard, the fruit sources that have been reported are green apple, grapes, pineapple, guava, pomegranate peel, mulberry root bark and twigs, quince seeds, strawberry leaves and branches, coconut liquid endosperm, tomato skin, and mango peel. Vegetable sources include ginger, marjoram, onion, and chili pepper. Plant and herb sources include mangrove plant leaves, oregano herb aerial parts, citronella hydrosols, cinnamon, purslane, mate, green tea leaves, clove extract, aloe, and stevia plant leaves [3,14–16]. Other compounds, such as 4-hexylresorcinol (4HR), manuka honey, egg white, cod fish skin, buffalo whey, and blue mussels have also shown to be effective inhibitors of PPO [17,18]. While their primary goal is to maintain color and prolong shelf life, anti-browning treatments should not adversely affect other properties, components, or sensory attributes [3,19].

Although several investigations have been conducted to determine the suitability of certain varieties for the production of Minimally Processed Products by monitoring their resistance to browning [3,19–22], there is no information regarding the evaluation of the anti-browning methods, nor their impact on the sensory quality of developed potato products using Colombian varieties. Therefore, in this study, the objective was to evaluate different anti-browning methods on the quality of Colombian varieties of potato as raw materials for the development of Minimally Processed Products, considering sensory impact.

2. Materials and Methods

2.1. Materials

This research used four potato varieties from Colombia of broad commercial participation, namely, ICA-Nevada, Parda Pastusa, Diacol Capiro, and Sabanera or Tuquerreña. For practical reasons, they will subsequently be referred to as: Nevada, Pastusa, D. Capiro and Sabanera (Figure 1). The potatoes used in this study had no mechanical affectations and were free of damage caused by pathogens and insects. They were purchased in the Central Mayorista de Antioquia (Medellín, Colombia). In addition, the potatoes were medium and large in size, corresponding to diameter sizes between 45 and 90 mm based on Colombian Technical Standard NTC 341 (a food industry classification for potatoes for consumption). The study was conducted during the potato's dormancy stage, when the tubers did not show sprout growth. The raw material was stored under refrigerated conditions ($4 \pm 2^\circ\text{C}$) in a cold storage unit (Haceb H7164NT44, Copacabana, Colombia) for approximately 12 h until analysis. Then, the potatoes were subjected to washing with tap water and disinfection processes using a sodium hypochlorite solution at a concentration of 50 ppm. All the reagents (Merck KGaA, Darmstadt, Germany) used in the experiments were of analytical grade.

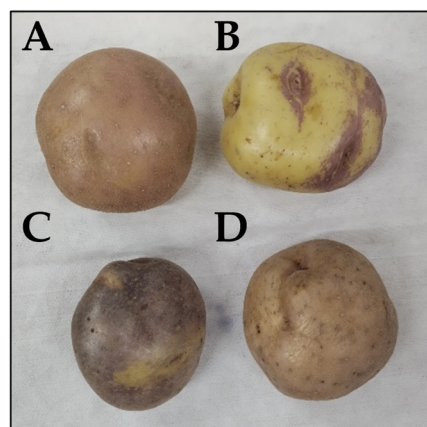


Figure 1. (A) Diacol Capiro, (B) Nevada, (C) Sabanera, and (D) Pastusa potato varieties.

2.2. Variety Characterization

2.2.1. Physicochemical Characterization

The following analyses were performed on the fresh potatoes: Moisture content (%) was determined by the gravimetric method in an air oven with drying at 105°C to a constant weight according to the AOAC method of analysis. pH was determined using a pH meter (Hanna Instruments pH meter, HI3220, Washington, DC, USA). Total acidity was assessed through titration with NaOH (0.1 N) using phenolphthalein as an indicator until all the organic acids were neutralized. It is expressed as a percentage of ascorbic acid. The total soluble solids (TSS) were determined through refractometer readings (Brixco Instruments, Berlin, Germany). Vitamin C was calculated by titration of the potato samples with a 2,6-dichlorophenolindophenol standard solution in an acid environment, and the results are expressed as mg/100 g [23,24]. All analyses were performed in triplicate.

2.2.2. Color Assessment and Browning Index (BI)

The color assessment of the potato flesh (pulp) was determined according to the CIEL*a*b* methodology [25], using a colorimeter Color Reader CR-20 Konica Minolta (Osaka, Japan) with an illumination angle of 8° . For the analysis, a longitudinal cut was first made to the potato, and measurements were immediately taken at the four opposite points of the transverse and longitudinal axes, together with the center of the potato. Additionally, three samples were used for each variety. The overall average of the samples analyzed was taken. The browning index (BI) was calculated for a 70 min period by performing

color measurements every 10 min. For this purpose, Equation (1) was used, which depends on variable X , represented in Equation (2), obtained using color parameters (a^* , b^* , L^*). Similarly, the color difference (ΔE) was determined using Equation (3), employing the same parameters [11].

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

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

$$\Delta E = \sqrt{(\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})} \quad (3)$$

2.2.3. Polyphenol Oxidase (PPO) Activity and Total Phenolic Content (TPC)

PPO activity was assessed by spectrophotometrically monitoring the formation of quinones, with absorbance measured at a wavelength of 410 nm for 120 s [26]. Regarding total phenolic content, it was determined using the Folin–Ciocalteu reagent (Merck KGaA, Darmstadt, Germany), followed by incubation in the dark and a measurement of absorbance at 725 nm (CARY 50 BIO, UVvis, California, USA) with distilled water as the blank [23]. The result was calculated using a calibration curve based on gallic acid. The results are expressed as mg equivalents of gallic acid per 100 g of fresh sample (mg GAE/100 g).

2.2.4. Microstructural Characterization

The microstructure analysis was performed using Scanning Electron Microscopy. Samples from each variety were cut and air-dried ($25 \pm 2^\circ\text{C}$, 2 h). Subsequently, they were placed on aluminum disks previously prepared with double-sided graphite tape. Then, gold was deposited on the surface of the samples using low-vacuum plasma or sputter coating. The gold-coated samples were then placed in the JEOL JSM64990LV microscope (Tokyo, Japan) chamber for the micrographic visualization of the potato microstructure [27].

2.3. Anti-Browning Treatments

The washed and disinfected potatoes were peeled and cut into pieces of $1 \times 1 \text{ cm}^2$, approximately. Then, they were subjected to different anti-browning treatments, that is, three immersion processes in technological coadjutants and one control process. The potato pieces were placed in a desiccator containing the anti-browning solution, and a potato–solution ratio of 1:1 (without agitation) was maintained to ensure adequate submersion. All immersions were conducted for 3 min, after which the potatoes were removed from the container, drained, and excess moisture was eliminated using a manual vegetable spinner. The treatments used were based on previous studies and slightly modified, as follows:

- CC: Immersion in water as a control. Distilled water was used to submerge the potato pieces as a control treatment, keeping the same ratio, immersion time, and subsequent activities.
- AE: Immersion in garlic extract criollo variety at 0.5%. The methodology was based on [28]. Firstly, a preliminary test was made using a national variety and a foreign variety (criollo and chino garlic varieties). Since the criollo variety showed better anti-browning capacity, it was used for the study. Then, 100 g garlic clove was homogenized with distilled water to obtain a solution mixture containing 0.5% (m/m), and the homogenate was filtered. The supernatant was collected to be used as a fresh garlic extract [26].
- AA: Immersion in ascorbic acid at 1.0%. The methodology was based on [19]. Firstly, a 1% ascorbic acid solution was prepared with distilled water. The ascorbic acid concentration was selected from a preliminary test comparing different concentrations. The solution was assisted in the preparation through homogenization using a glass bar.

- AC: Immersion in citric acid at 1.0%. The methodology was based on [19,29]. Firstly, a 1% citric acid solution was prepared with distilled water. The citric acid concentration was selected from a preliminary test comparing different concentrations. The solution was assisted in the preparation through homogenization using a glass bar.

The treatments were applied immediately after the solutions were prepared, and treated samples were packed in polyethylene bags. Fresh-cut potato pieces from each selected variety were randomly split into four groups, each containing approximately 100 g. Therefore, for each variety, there were four bags: AC, AA, AE, and CC. The samples were stored under refrigerated conditions at 4 ± 2 °C. Analyses of TPC, CIEL*a*b* color, and browning index (BI) were conducted at 0, 5, 10, and 15 days of storage. The analyses were performed in triplicate, and the results are expressed as the mean $\pm$ standard deviation.

2.4. Anti-Browning Treatment Selection

Firstly, considering the results obtained for the four potato varieties (Nevada, Pastusa, Capiro, and Sabanera) in terms of physicochemical characterization, color assessment, browning index, polyphenol oxidase activity, and total phenolic content, one variety was selected to continue the development of the research. Secondly, taking into account the results for the three anti-browning treatments (AA, AC, and AE), concerning color assessment, browning index, and total phenolic content, one treatment was selected for continuation with the sensory analysis.

2.5. Sensory Analysis

The sensory analysis of the fresh and treated potatoes was performed by the Sensory Analysis Laboratory of the Universidad de Antioquia (Medellín, Colombia). One treatment (AA, AC, or AE) was selected as having the best anti-browning effect, considering minimal color change during storage. The sensory evaluation was performed using a multidimensional profile approach (NTC 3932 (1996): ISO 11035 (1994)) [30] with an expert panel. Relevant descriptors were identified in terms of flavor (F), odor (O), and texture (T) to provide the maximum amount of information about the sensorial attributes of the samples and define their sensory profiles. The samples were subjected to a cooking process, in which water was brought to boiling, after which the potatoes were added in a 1:10 ratio, allowing them to cook for 16 min approx., at an average temperature of 88 °C. The scale employed to categorize the intensities of the descriptors ranged from 0 to 5, where 0 indicates absence, 1 is very weak, 2 is weak, 3 is moderate, 4 is strong, and 5 is intense. The overall quality was also evaluated on a scale of 1 to 3, where 1 indicates low quality, 2 indicates medium quality, and 3 indicates high quality. The samples were allowed to cool to room temperature (~ 25 °C) and the analyses were performed in duplicate.

2.6. Statistical Analysis

The results of each analysis are presented as means $\pm$ standard deviation based on at least three measurements. An analysis of variance (ANOVA) along with Fisher's Least Significant Difference (LSD) test was employed to identify significant differences among the means at a significance level of $p < 0.05$ using Statgraphics Centurion XVI software (Statistical Graphics Corporation, Ver. 16.0.07, Rockville, MD, USA). Considering the results obtained from the initial characterization of each variety and the subsequent results obtained from the three anti-browning treatments applied to the varieties (CC, AE, AA, AC), i.e., in terms of the color assessment and browning index, one variety was selected to continue with the development of the research. Once one potato variety and one anti-browning treatment were selected, the sensory impact of the selected immersion treatment was evaluated.

3. Results and Discussion

3.1. Physicochemical Characterization of Varieties

Table 1 shows the results for the physicochemical characterization of the varieties. This information is consistent with previous reports for the same varieties, which indicate moisture percentages ranging from 63.2 to 86.9% [31]. The values obtained for the moisture content varied, with D. Capiro and Pastusa being the varieties that exhibited the highest moisture content, while Sabanera had the lowest. The differences in moisture content may be attributed to the maturity stage of the tubers, climate, soil, type of cultivation, or storage conditions. The pH, soluble solids, and titratable acidity matched those reported in the literature by various authors [5]. In this study, the Nevada and Pastusa varieties exhibited the highest levels of vitamin C, which were significantly different from those of the other two varieties evaluated. Ascorbic acid is the main acid present in potatoes [32]. Fresh potatoes have a variable concentration of ascorbic acid that has been reported to reach up to 50 mg/100 g of fresh weight when freshly harvested [10]. Significant vitamin C variations due to genotype, environment, and the interactions between these factors has been found and reported previously by Burgos (2009) [33], who analyzed the ascorbic acid concentration of 25 Andean potato varieties. Total phenolic content (TPC) will be subsequently discussed.

Table 1. Physicochemical characterization of four Colombian potato varieties.

Variety	Moisture (%)	pH	TPC (mg GAE/100 g)	Total Acidity (%)	TSS (°Brix)	Vitamin C (mg/100 g)
Nevada	77.99 ± 1.20 ^b	6.76 ± 0.05 ^c	117.27 ± 3.66 ^d	0.12 ± 0.02 ^a	4.23 ± 0.12 ^a	41.83 ± 0.14 ^c
Pastusa	82.43 ± 0.86 ^c	6.57 ± 0.02 ^a	43.38 ± 1.89 ^a	0.10 ± 0.01 ^a	4.03 ± 0.12 ^a	37.70 ± 5.66 ^{b,c}
D. Capiro	80.92 ± 0.98 ^c	6.66 ± 0.07 ^b	51.04 ± 1.67 ^b	0.16 ± 0.01 ^b	4.10 ± 0.12 ^a	30.83 ± 0.68 ^b
Sabanera	73.79 ± 1.41 ^a	6.77 ± 0.03 ^c	63.79 ± 2.85 ^c	0.16 ± 0.01 ^b	4.16 ± 0.12 ^a	22.92 ± 4.79 ^a

TPC = total phenolic content; GAE = gallic acid equivalent; TSS: total soluble solids; Different letters in the same column indicate significant differences ($p < 0.05$).

3.2. Color Assessment and Browning Index (BI)

Table 2 shows the results for the color parameters of potato flesh for the different varieties, determined according to the CIEL*a*b* scale. The L* parameter (lightness or darkness) varies between 0 (black) and 100 (white); therefore, the data obtained for all varieties exceed the value of the middle of the scale, indicating a higher luminosity in the samples, particularly in the Diacol Capiro and Nevada varieties. The a* parameter represents positive values (+a*) for red and negative values (−a*) for green, suggesting that the flesh of the samples has a reddish hue, more pronounced in the D group (Capiro and Sabanera varieties). Finally, the b* parameter can have positive (+b*) and negative (−b*) values, corresponding to the yellow and blue components, respectively. Since the samples showed values in the positive range of b*, a notable yellow hue characteristic of the potatoes was observed that was more pronounced in the D. Capiro and Sabanera varieties [10]. White- and yellow-fleshed potatoes, such as those explored in this study, have a composition similar to carotenoids, and the yellow color is mainly attributed to higher levels of xanthophylls [5].

Figure 2 presents the mean values of the color parameters in terms of L*, a*, and b* during 70 min of air exposure after making a cross-section. Figure 2A shows that the L* parameter decreases, resulting in a loss of lightness, while simultaneously the a* chromatic space increases (Figure 2B), becoming more reddish. The appearance of red hues on the surface of the flesh is associated with oxidation and, in turn, related to the activity of the PPO enzyme in potatoes [8]. It is observed that the Sabanera variety showed statistically significant differences compared to the other varieties, achieving the lowest value of L* and the highest value of a*. Regarding the b* parameter, it tends to shift toward blue coloration as time progresses. This color-change behavior has been widely associated

with the oxidation of phenolic compounds of many other potato varieties [5]. In this regard, Figure 3 shows the changes in colors of potato flesh at 0, 10, 20, 30, 40, 50, 60, and 70 min, after making a cross-section. The darkening of the flesh is observed as time goes by, and this browning is associated with changes in the L^* , a^* , and b^* parameters, as previously reported. However, during the first few minutes, the color changes are not easily perceived by the human eye, which is the opposite of what was seen in the colorimetric analysis. ΔE represents the color difference in the measurements between two colors, and it is considered perceptible to the human eye when ranging from 4 to 6. The appearance of potatoes, including their color and surface, influences the quality perception of fresh horticultural products and consumer purchase decisions [3].

Table 2. Color parameters of potato flesh from different varieties.

Variety	Color Parameters CIE $L^*a^*b^*$		
	L^*	a^*	b^*
Nevada	$68.54 \pm 1.93^{a,b}$	$1.50 \pm 0.46^{a,b}$	23.34 ± 0.89^a
Pastusa	67.20 ± 2.57^a	1.48 ± 0.26^a	24.36 ± 0.43^b
D. Capiro	71.20 ± 1.51^b	2.34 ± 0.61^c	26.74 ± 0.60^c
Sabanera	67.46 ± 2.15^a	$2.04 \pm 0.17^{b,c}$	27.00 ± 0.32^c

Different letters in the same column indicate significant differences ($p < 0.05$).

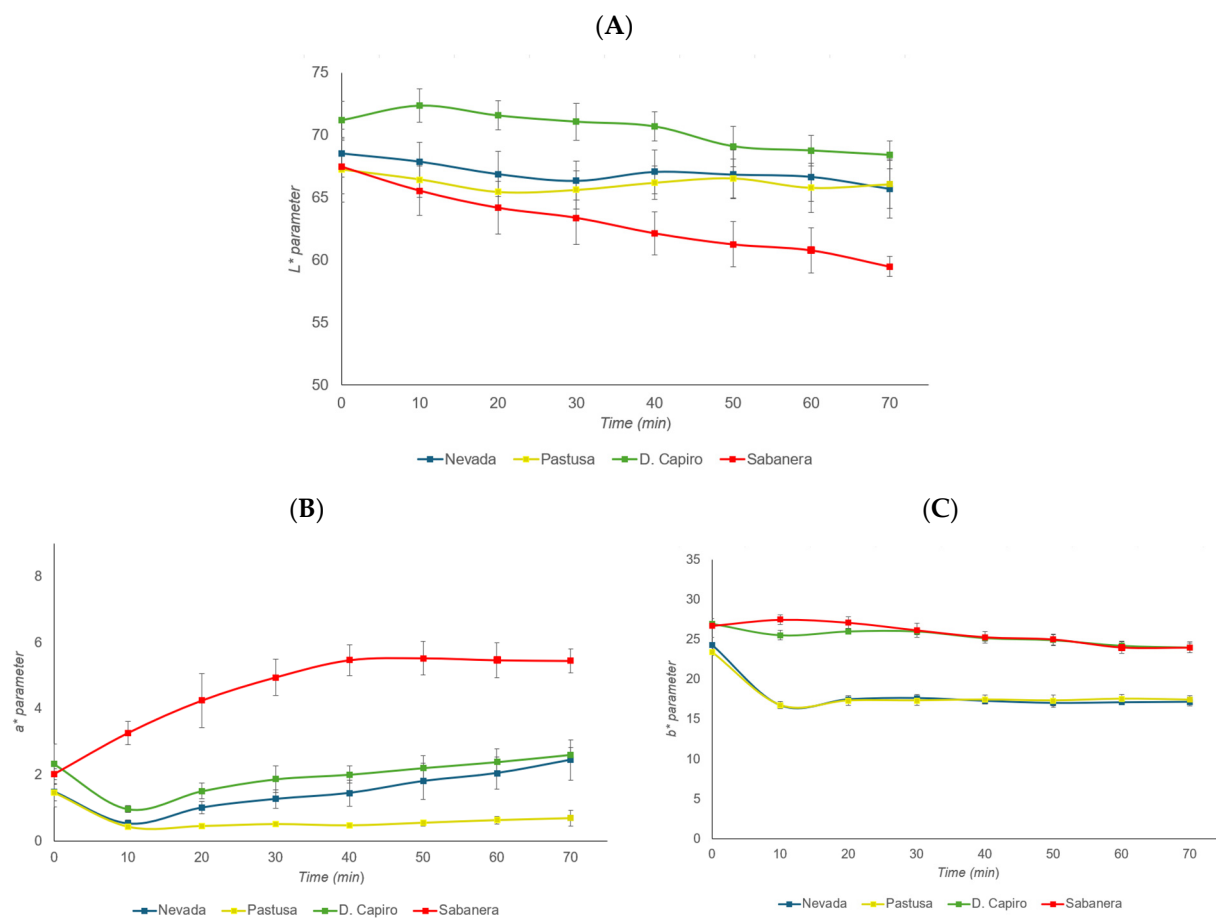


Figure 2. Changes in color parameters L^* (A), a^* (B), and b^* (C) of potato flesh over time.

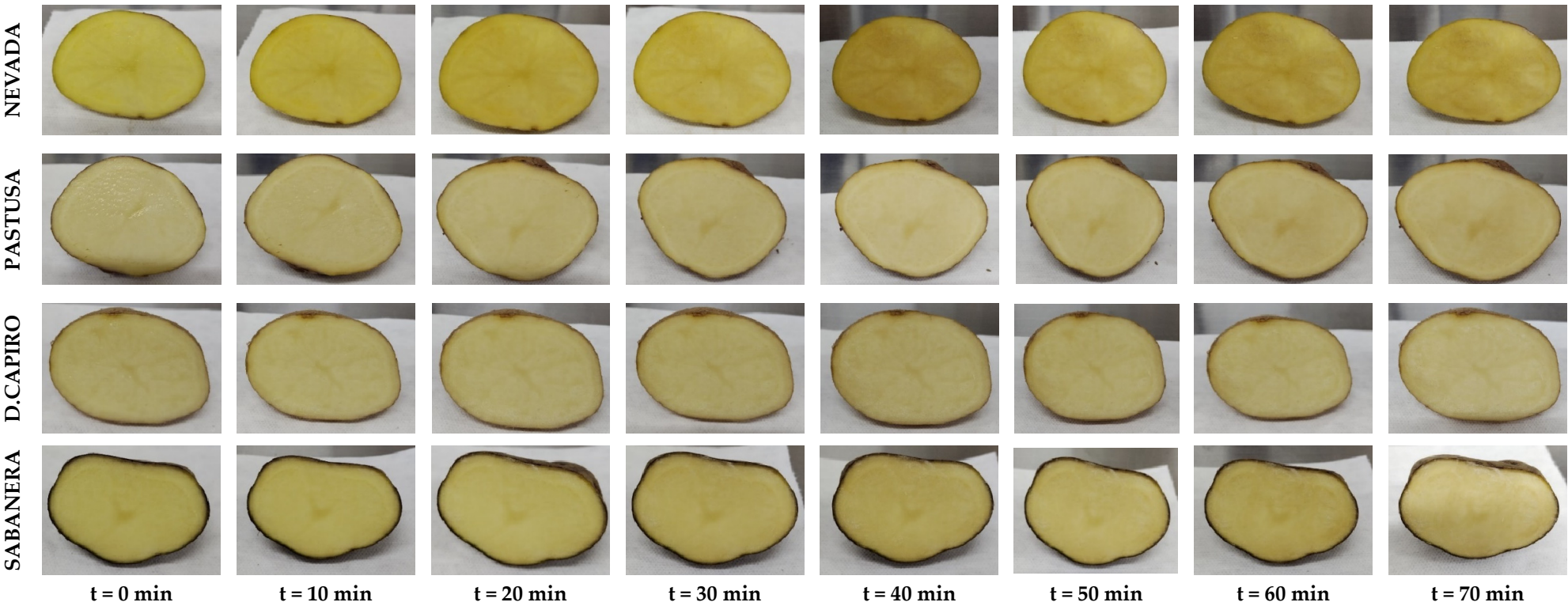


Figure 3. Changes in color of potato flesh over time.

Figure 4 shows the browning index of the studied varieties over time. The potato varieties examined in this experiment showed variations in their chemical characteristics that were noticeable when they were cut, as well as differing changes in color and appearance during storage after minutes of air exposure. When a cut is made in a potato, a cellular rupture occurs, which causes the phenolic compounds of the tuber (contained in cell vacuoles, mainly in the epidermis) to come into contact with the PPO, causing darkening of the flesh. Thus, the browning index has a strong correlation with PPO activity [5,11]. According to the figure, the highest browning index was for the Sabanera variety, which maintained statistically significant higher values than the rest of the varieties for the entire analysis time. This was followed by the D. Capiro potato, which showed a medium browning index compared to the others. Finally, the Pastusa and Nevada varieties showed a lower degree of browning index than the rest. From Table 1, it can be seen that Pastusa is the variety with the lowest concentration of TPC, and therefore the least capacity to react with PPO. The behavior of the Nevada variety is somewhat surprising, considering that it contains higher levels of TPC, second only to the Sabanera variety; therefore, higher levels of browning index were expected. The substrate content of the PPO enzyme is important, but also other aspects are relevant when evaluating enzymatic browning in different varieties. In relation to this, some authors have evaluated the suitability of certain cultivars regarding enzymatic browning. Hasbún et al. (2008) evaluated some physical–chemical properties and quality parameters for the industrial use of four potato varieties from Costa Rica, finding that the quality characteristics were determined by the variety and the growing conditions of the tuber [21]. On the other hand, considering that in Argentina the fresh market is dominated by the Spunta variety, which is the one generally used as a minimally processed product, Garcia-Procaccini and Capezio (2019) evaluated the suitability of other potato varieties for the fresh market. Their results confirmed the existing differences between potato varieties in terms of postharvest qualities and the need to extend the work to other varieties in order to have more genotypes available for processing [19]. Ingallina et al. (2020) carried out the characterization of Italian potato cultivars for industrial use, promoting their preservation and utilization as high-quality raw materials in the food industry. The authors found that the Roseval and Rubra varieties contained an elevated content of citric acid, which was involved in the inhibition of enzymatic browning in fresh-cut potatoes [34].

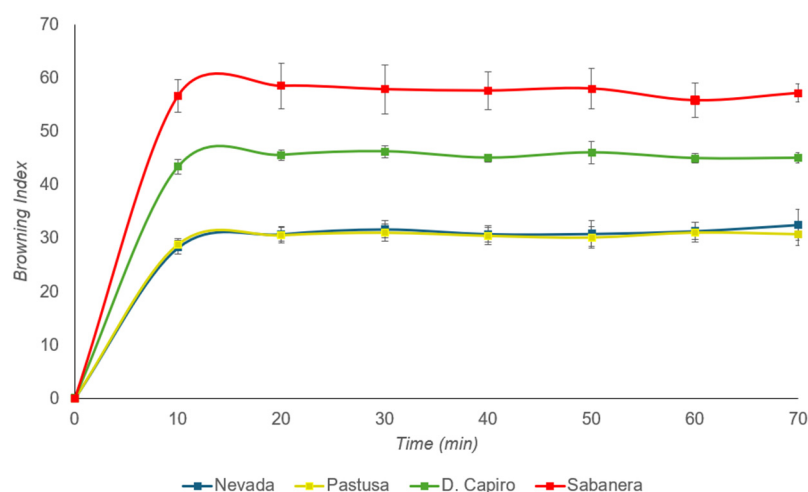


Figure 4. Browning index of potato varieties over time.

In another study, Suárez et al. (2016) carried out the phenotypic, biochemical, and molecular characterization of potato varieties native to Argentina, analyzing their enzymatic browning. The authors reported that native varieties show low browning compared to commercial varieties. PPO activity showed significant differences between the varieties [20], evidencing that enzymatic browning is variable-dependent. In this regard, González et al. (2020) evaluated the reduction in enzymatic browning of potato tubers by

specifically editing a polyphenol oxidase gene via its ribonucleoprotein complexes. The results indicated that mutations induced in the alleles resulted in a reduction of up to 69% in tuber PPO activity and a 73% decrease in enzymatic browning compared to the control. Therefore, the authors demonstrated that the method can be applied to create potato varieties with lower enzymatic browning through the targeted editing of a specific member of the PPO gene family [22].

3.3. Polyphenol Oxidase (PPO) Activity and Total Phenolic Content (TPC)

Figure 5 shows the PPO activity of the four potato varieties. PPO is an oxidoreductase with copper as a prosthetic group. This enzyme catalyzes the o-hydroxylation of monophenols and the oxidation of o-diphenols into o-quinones with oxygen as the primary oxidant [35]. The change in absorbance is directly related to the enzymatic activity present in the analyzed potato varieties. It is observed that the Sabanera variety shows the highest enzymatic activity at the end of the study, followed by the Nevada variety, while the D. Capiro and Pastusa varieties exhibit lower activities. This is closely related to what has been described in previous studies, which explain that PPO activity varies depending on the potato variety [6]. Polyphenol oxidases in potatoes constitute a large gene family, with some appearing to be much more central to browning than others [5]. Specifically in potato, researchers have established optimal pH values between 6.0 and 7.5 for the maximum activity of PPO [25]. In addition to the activity of the PPO enzyme, the availability of phenolic compounds present in the food matrix that act as substrates, as well as the amount of enzyme, are factors considered in processing. This is because having a greater quantity of these components generally tends to increase the rate of browning [36]. Therefore, a concern regarding the development of potatoes with high polyphenol content is the possibility of unacceptable levels of browning or darkening after cooking, as suggested by earlier studies [5]. The activity of PPO also affects the flavor and aroma of horticultural products, as phenolic compounds contribute to bitter, sweet, pungent, or astringent tastes in fruits, vegetables, and spices [35].

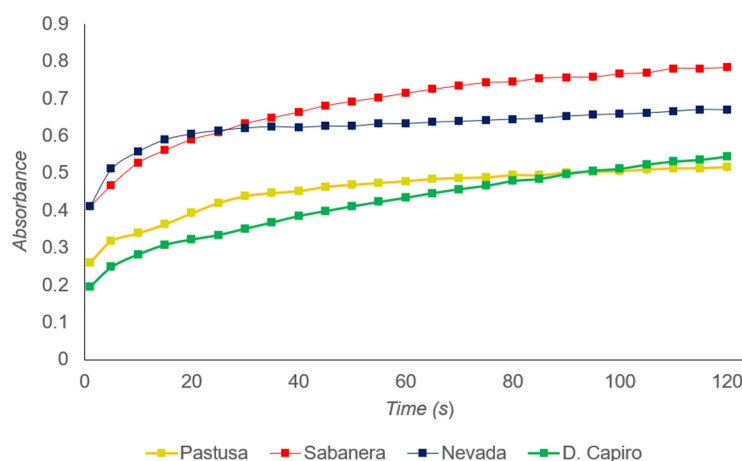


Figure 5. Activity of the enzyme polyphenol oxidase in potato varieties.

Table 1 shows the total phenolic content (mg GAE/100 g) of each potato variety. The Nevada variety showed a significantly higher value than the other varieties, followed by the Sabanera variety. In contrast, the Pastusa variety showed the lowest content, followed by the Diacol Capiro variety. Statistically significant differences in TPC were observed among all varieties. It has been reported that the total phenolic content in potatoes is composed of chlorogenic acids, such as caffeic and cinnamic acids, p-coumaric, ferulic, and synaptic acids [37]. These, along with vitamin C content, are responsible for the antioxidant capacity of the tuber. Considering the high global consumption of potatoes, they are an important source of antioxidants, with polyphenols being recognized as the most abundant antioxidants in the diet [38]. Other studies have reported TPC values

in the range of 94 to 844 mg GAE/100 g db [39,40] for different varieties. In our study, the higher TPC values for the Nevada and Sabanera varieties can be explained by their composition. This is also reflected in the color of their flesh and skin, as they contain specific phenolic compounds. Yellowish-cream-fleshed potatoes such as Nevada are associated with carotenoid content [23].

The second highest value for TPC corresponded to the Sabanera variety. It is characterized by purple-to-dark-blackish skin with a cream color around the eyes (Figure 1C). Purple- and red-fleshed potatoes are rich in phenolic acids and anthocyanins, which are linked to their color. These compounds serve as antioxidants and offer various health benefits [5]. Among the most abundant phenolic compounds present in these potato varieties are chlorogenic acid, caffeic acid, quinic acid, and L-tyrosine. In smaller proportions, notable compounds include synapic acid, vanillic acid, ferulic acid, and protocatechuic acid, among others. Some studies conducted with purple- and red-fleshed potatoes have reported that the concentration of total phenolic compounds and anthocyanins varies from 76 to 180 mg and from 11 to 174 mg per 100 g of fresh potato, respectively, depending on the location and genotype [32]. It is worth noting that the content found in this study is a bit lower than the previously reported levels because the Sabanera potato, while having purple skin, has cream-colored flesh. It is reported that almost 50% of phenolics are located in the peel and adjoining tissues, and their concentration decreases towards the center of the tuber [5].

When comparing TPC (Table 1) and PPO activity (Figure 5), it is noticed that the Sabanera variety has the highest enzymatic activity and the second highest polyphenol content—after the Nevada variety—leading a higher degree of browning, which was evident in the browning index (Figure 4) as well as in the change in the color of potato flesh over time, perceived by the human eye (Figure 3). The browning of tissues is also promoted by peroxidase (POD), which catalyzes the oxidation and polymerization of phenolic compounds, resulting in the formation of brown substances [8].

When it comes to the Nevada variety, which has the highest TPC and the second highest PPO activity, the browning index was the lowest, alongside the Pastusa variety. It was expected that the Nevada variety would show a higher degree of browning. However, PPO has multiple substrates, with chlorogenic acid (a phenolic compound) and tyrosine (an amino acid) being the primary two in potatoes [5]. Although many studies have reported a positive correlation between the browning index, TPC, and PPO activity in horticultural products, no direct correlation was found between them in this study. This finding is consistent with the results of Cantos et al. (2002) [41], who reported that the levels of total phenolics, chlorogenic acid, and polyphenol oxidase measured in their study did not correlate with the degree of browning observed in fresh-cut potatoes [5]. It is hypothesized that phenylalanine ammonia lyase (PAL) and peroxidase (POD), two enzymes involved in the browning of plant tissues, may contribute to the variable response observed in fresh-cut potato tissues. Additionally, PPO activity varied in different locations of the tubers, suggesting that substrate and enzyme concentrations may also play a role. It is possible that even a small amount of PPO is sufficient to cause visible discoloration in potato tubers, although in some cases, a higher concentration of PPO may be required to produce a more pronounced effect, depending on other factors such as substrate availability and environmental conditions.

3.4. Microstructural Characterization

Figure 6 shows the micrographs obtained for the fresh potatoes of the Nevada (A), Pastusa (B), Diacol Capiro (C), and Sabanera (D) varieties, subjected to magnifications of 300× and 700×. In all the micrographs, the parenchyma of the potato tuber is observed with a preserved cell wall arrangement. These structures are generally composed of the middle lamella—primarily made up of pectic substances—and the primary cell wall—composed of cellulose, hemicellulose, glycans, and pectins [42]. The cells of the potato tissue containing starch granules are observed, showing variable sizes, ranging from 4 to 60 µm for the

Nevada variety, 6 to 49 μm for the Pastusa variety, 6 to 60 μm for the Diacol Capiro variety, and 3 to 57 μm for the Sabanera variety. Overall, a wide variability in granule sizes was observed, which, according to Simkova et al. (2013), is characteristic of starch derived from potatoes [43]. Other granule sizes reported previously by other authors range between 1 and 110 μm [5]. Additionally, it is noted that, across the different potato varieties, the larger granules are ellipsoidal, while the smaller granules have more rounded shapes, which coincides with previous reports [27]. Finally, the small filamentous structures, especially visible at 300 $\times$ magnification in the Nevada potato variety, could denote small particles such as cellular debris, glycoproteins, or polysaccharides [42].

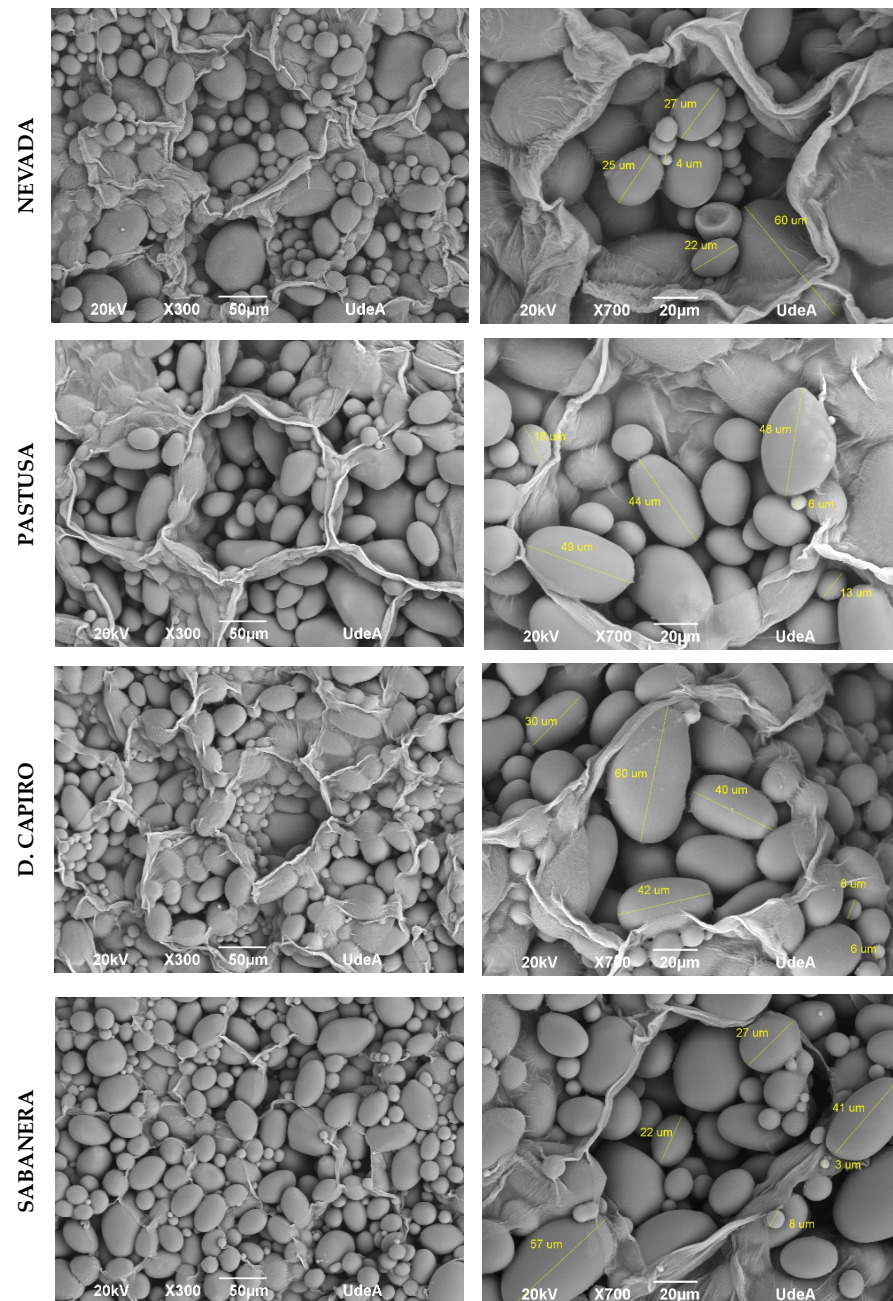


Figure 6. Scanning electron micrographs of the potato varieties at 300 $\times$ (**left**) and 700 $\times$ (**right**).

3.5. Evaluation of Anti-Browning Treatments

Considering the results of the initial characterization, particularly in terms of the browning index and PPO activity, the Sabanera variety showed the least suitability for MPP

development. Therefore, the experiment continued using the remaining three varieties. Tables 3–5 show the color change (ΔE) for the Nevada, Pastusa, and D. Capiro potato varieties. The results show that the immersion in water as a control treatment, in which the oxygen level in the environment is reduced [44], was not enough to maintain the color parameters of the potato from day 0. The results showed statistically significant differences in color change across all varieties after the immersion treatments in the anti-browning compounds. Thus, dipping potato pieces in water allowed severe browning to develop after 15 days of storage at 4 °C. As expected, AC, AA, and AE showed lower values from day 0.

Table 3. Color change (ΔE) for the Nevada potato variety.

ΔE Nevada	Storage Time (Days)			
	0	5	10	15
CC	13.53 $\pm$ 0.95 ^c	11.87 $\pm$ 1.38 ^c	11.12 $\pm$ 0.93 ^a	15.79 $\pm$ 0.67 ^c
AC	8.57 $\pm$ 1.13 ^b	7.08 $\pm$ 1.30 ^a	11.09 $\pm$ 1.33 ^a	10.21 $\pm$ 0.13 ^a
AA	6.17 $\pm$ 0.78 ^a	9.78 $\pm$ 1.48 ^b	11.46 $\pm$ 1.25 ^a	14.45 $\pm$ 0.33 ^b
AE	9.22 $\pm$ 1.40 ^b	8.25 $\pm$ 1.88 ^a	10.03 $\pm$ 1.84 ^a	14.24 $\pm$ 0.61 ^b

CC: control; AC: citric acid 1.0%; AA: ascorbic acid 1.0%; AE: garlic extract 0.5%; Different letters in the same column indicate significant differences ($p < 0.05$).

Table 4. Color change (ΔE) for the Pastusa potato variety.

ΔE Pastusa	Storage Time (Days)			
	0	5	10	15
CC	9.96 $\pm$ 0.87 ^b	6.13 $\pm$ 1.87 ^{a,b}	11.32 $\pm$ 0.95 ^b	14.14 $\pm$ 2.54 ^b
AC	3.67 $\pm$ 1.74 ^a	4.03 $\pm$ 1.08 ^a	7.83 $\pm$ 2.90 ^a	12.83 $\pm$ 1.22 ^a
AA	2.81 $\pm$ 1.05 ^a	7.56 $\pm$ 2.80 ^c	11.26 $\pm$ 1.90 ^b	14.95 $\pm$ 0.94 ^b
AE	3.96 $\pm$ 1.30 ^a	8.23 $\pm$ 1.64 ^c	9.25 $\pm$ 1.28 ^{a,b}	15.73 $\pm$ 0.08 ^c

CC: control; AC: citric acid 1.0%; AA: ascorbic acid 1.0%; AE: garlic extract 0.5%; Different letters in the same column indicate significant differences ($p < 0.05$).

Table 5. Color change (ΔE) for the D. Capiro potato variety.

ΔE D. Capiro	Storage Time (Days)			
	0	5	10	15
CC	12.19 $\pm$ 2.36 ^c	7.88 $\pm$ 1.16 ^c	10.32 $\pm$ 1.60 ^b	11.34 $\pm$ 1.10 ^b
AC	4.60 $\pm$ 0.59 ^{a,b}	4.82 $\pm$ 1.95 ^a	8.92 $\pm$ 1.30 ^a	8.58 $\pm$ 1.37 ^a
AA	3.17 $\pm$ 1.87 ^a	5.09 $\pm$ 0.97 ^{a,b}	13.98 $\pm$ 1.75 ^b	12.26 $\pm$ 0.56 ^b
AE	4.85 $\pm$ 0.82 ^{a,b}	6.41 $\pm$ 2.94 ^{a,b}	7.08 $\pm$ 1.72 ^a	11.53 $\pm$ 0.23 ^b

CC: control; AC: citric acid 1.0%; AA: ascorbic acid 1.0%; AE: garlic extract 0.5%; Different letters in the same column indicate significant differences ($p < 0.05$).

At the end of the storage, AC showed the least color change of all the varieties, followed by ascorbic acid and finally garlic extract. In this context, garlic extract has shown different behaviors across both substrate conditions and heat treatment temperatures [26]. The highest inhibition activity of garlic extract was observed for a heat-treated sample at 100 °C [26]. On the other hand, the fresh garlic extract did not exhibit any inhibitory effect on PPO [26], coinciding with the results of this study. The observation that garlic extracts treated at high temperatures exhibit a stronger inhibitory effect may be attributed to the increased kinetic energy of the reacting substances as the temperature rises, along with the denaturation of certain compounds that inhibit activity in garlic extracts at higher temperatures [26]. Many health properties of garlic and other *Allium* species, including the inhibitory action of their extracts, are attributed to their organosulfur compounds, particularly thiosulfates (R-S-S(O)-R') [45]. Diallyl thiosulfate (allicin) is one of the most

active compounds in garlic, accounting for 60–80% of the overall thiosulfates present or formed upon crushing garlic cloves.

Regarding ascorbic acid, it is the most commonly used anti-browning agent used today [11]. However, the literature presents contradictory results. According to Lim et al. (2019), ascorbic acid showed a percentage of inhibition between 41.7% and 64.1% with substrate concentrations ranging from 0.02 to 0.09% using methylcatechol and pyrocatechol [18]. On the other hand, some authors have stated that ascorbic acid can reduce the formed quinone to the original substrate (catechol) at high concentrations, that is, higher than 1.5%, while at lower concentrations it acts as competitive inhibitor [11]. Supporting this, Zhao et al. (2021) found that samples immersed in an isotonic solution of 5% ascorbic acid showed improved quality retention [44]. Regarding the mechanism, ascorbic acid prevents enzymatic browning by converting intermediate o-quinones back into their original phenolic compounds before they can react further to produce pigments [44]. Ascorbic acid may also reduce Cu^{2+} to Cu^{+} in PPO, thus retarding enzymatic browning. In addition, Lim et al. (2019), using chemical and natural anti-browning agents for the inhibition of enzymatic browning, reported that a mixed type of inhibition was observed for ascorbic acid. This type of inhibition can bind to both free enzymes (E) and also the enzyme–substrate complex (ES) [18]. A mixed inhibitor influences the substrate's affinity for the enzyme's active site by attaching to a site distinct from the active site, which then induces a conformational change in the enzyme's structure [18]. The results obtained are in contradiction with the classic theory of using redox substances as antioxidant agents. In this context, Bradshaw et al. (2001) evaluated the ability of ascorbic acid to induce the browning of (+)-catechin using wine as a model food matrix [46]. They reported a significant increase in absorbance, indicating that a byproduct of ascorbic acid oxidation is responsible for the initiation of browning [46]. However, it was not specified whether the browning of the products was due to the oxidation of catechin or its polymerization. In addition, when ascorbic acid is fully oxidized, it can no longer reduce quinones back to phenols and cannot effectively control enzymatic browning in fresh-cut fruits and vegetables over extended periods. Therefore, AA's ability to reduce browning in fresh-cut potatoes is limited [8]. Therefore, the inhibiting browning effect of AA in combination with other inhibitors would have better results. The inhibition of polyphenol oxidase activity by reducing agents alone or in combination has also been reported in the browning control of other fruits and vegetables [7,47,48]. Concerning citric acid, Tables 3–5 show the least color change (ΔE) for the Nevada, Pastusa, and D. Capiro potato varieties using this treatment. Citric acid is an inexpensive and fairly effective anti-browning agent that has previously been used alone or in combination with other substances in the fresh-cut processing of potatoes [49]. It acts as an acidulant or as a chelating agent [49]. It is a PPO non-competitive inhibitor [11]. However, it is unclear which of these roles has the predominant effect [49]. As Tsouvaltzis and Brecht (2017) have stated in their research, the inhibition of enzymatic browning by immersion in citric acid is not solely due to the pH reduction of the solution [49]. The effectiveness of an anti-browning agent is influenced by various factors, including its concentration and the pH of the solution. The authors noted that citric acid concentrations greater than 0.5% inhibited browning on the cut surfaces of fresh-cut potatoes while not impacting antioxidant content or PPO activity [49]. Studies have found that concentrations of 1 to 2% CA are effective in reducing browning in fresh-cut potato without affecting the nutritional quality in terms of antioxidant content or PPO enzyme activity [10,49]. It remains unclear whether this effect is due to the lower pH of the solution, which would indicate an acidulant effect, or the higher concentration used, which would suggest that more citrate molecules than thought are involved in chemical reactions with potato cellular components [49]. On the other hand, citric acid may potentially bind with phenolics, creating stable compounds that disrupt the phenylpropanoid pathway, which normally facilitates the oxidation of phenolics to o-quinones, leading to their polymerization into brown melanin pigments [49]. Furthermore, the formation of quinones, which are the main products of enzymatic oxidation, relies on both the phenolics from which they de-

rive and the pH of the tissue. It has been suggested that citric acid either interacts with phenolic substrates or the PPO enzyme to form complexes, or that it generates other compounds, indicating a role in inhibiting enzymatic browning beyond simply acting as an acidulant [49].

In addition, Figure 7 shows peeled and cut potato samples subjected to immersion in a 1% citric acid solution, which was the best anti-browning treatment for all varieties in terms of minimum change of color. Figure 8 shows the browning index during storage for all varieties, subjected to all treatments. It can be seen that for all treatments, including the control (CC), the level of darkening is dependent on the variety, resulting in less browning for the Diacol Capiro, followed by the Pastusa, and finally the Nevada variety, which showed the highest browning index. The level of browning being cultivar-dependent has also been demonstrated for other horticultural products such as pears, apples, mushrooms, and litchi fruit [50,51].

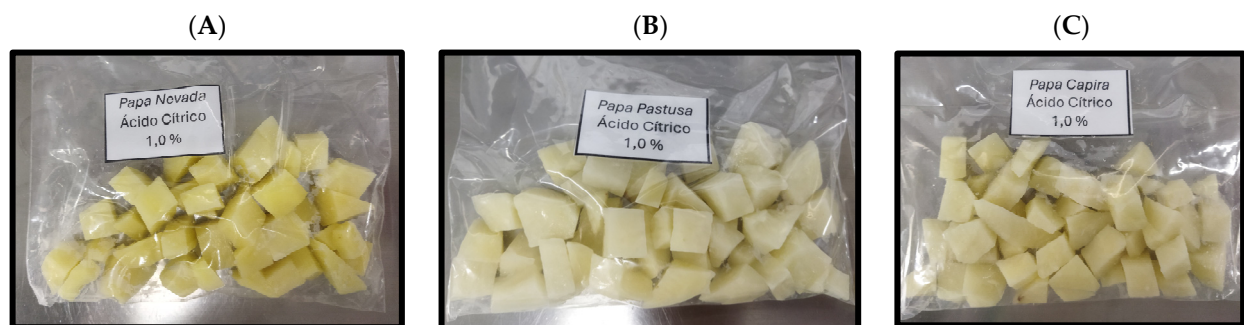


Figure 7. Peeled and cut potato pieces of (A) Nevada, (B) Pastusa, and (C) D. Capiro varieties subjected to immersion in a 1% citric acid solution (AC).

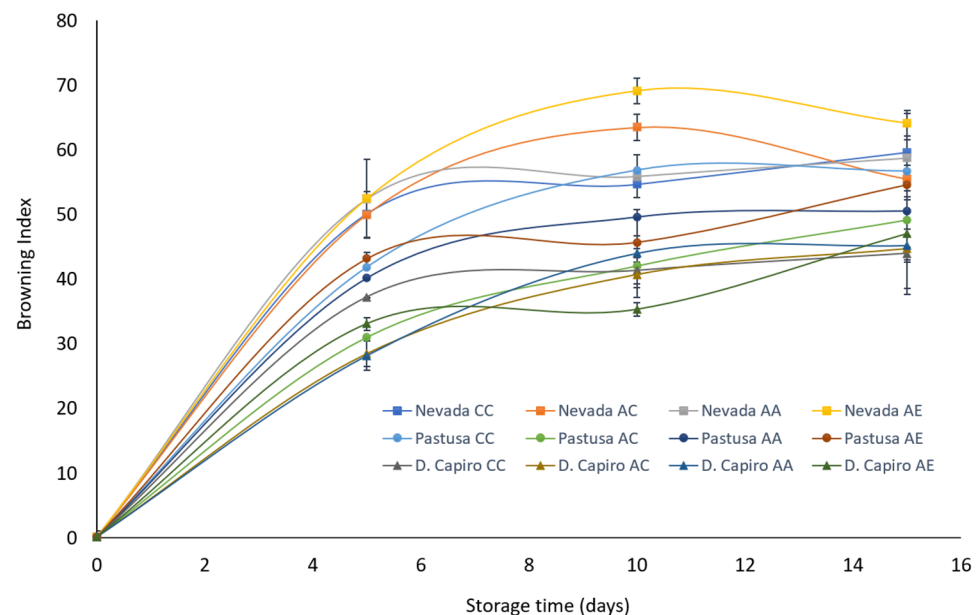


Figure 8. Browning index during storage for Nevada, Pastusa, and D. Capiro varieties subjected to all treatments: CC: control; AC: citric acid 1.0%; AA: ascorbic acid 1.0%; AE: garlic extract 0.5%.

During refrigerated storage, the change in TPC was also evaluated. Figure 9 shows the TPC content over 15 days for each treatment and the control. The variations in phenolic content among different varieties observed in the study may be attributed to the environmental conditions at the harvesting sites, which have been shown to impact the accumulation of phenolic compounds in potatoes [39]. In general, at the end of the storage period, the TPC was lower than the initial content; this was particularly noticeable in

the control samples (CC), while the AC-treated samples remained relatively stable over time. On the other hand, potatoes treated with AA showed a significant increase on certain days of the analysis. Meng LI et al. (2015) [52], when determining the polyphenol content during storage in garlic clove extract, found that the level of total polyphenols reached a maximum value and then decreased significantly. However, the Folin–Ciocalteu method for TPC is based on the ability of phenols to react with oxidizing agents. Thus, the reagent contains molybdenum and tungsten salts that react with any type of phenol to form phosphomolybdic–phosphotungstic complexes. Therefore, although this method provides a good estimate of total phenolic content for most plant matrices, it experiences interferences due to the presence of substances such as ascorbic acid. An increase in TPC over time after AA treatment in all experimental groups was also reported by Kita et al. (2013) [39], following the same Folin–Ciocalteu method.

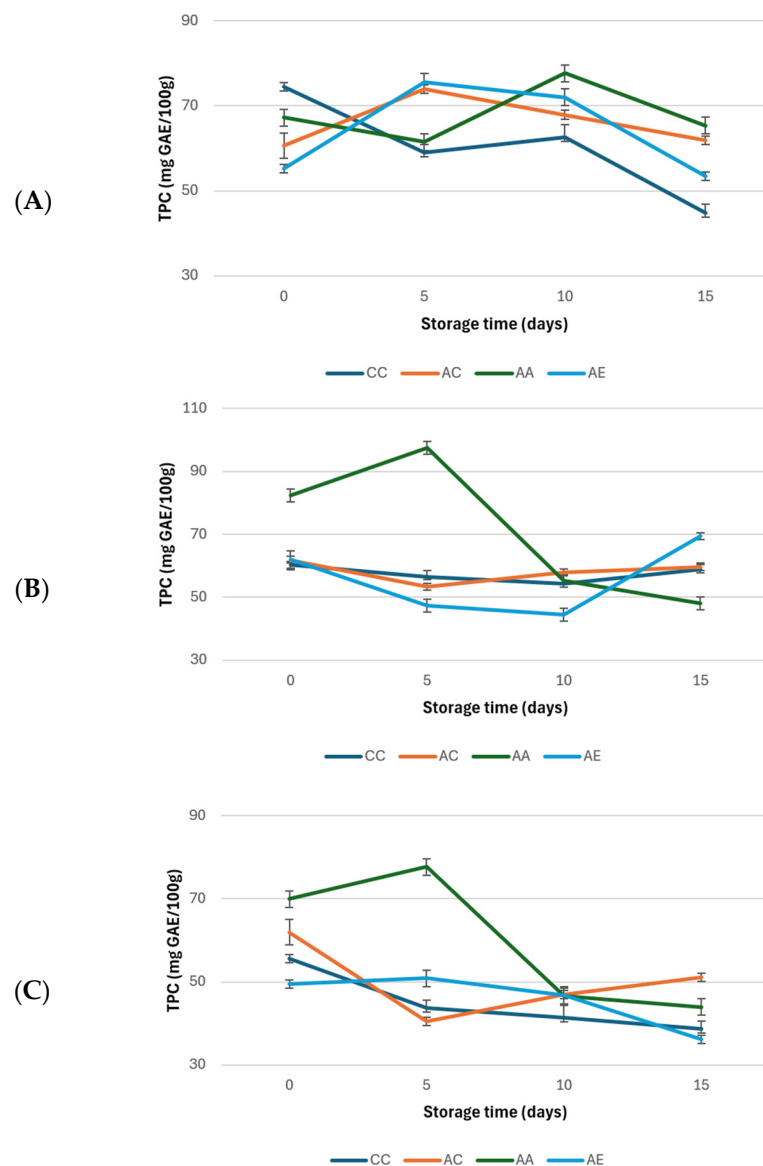
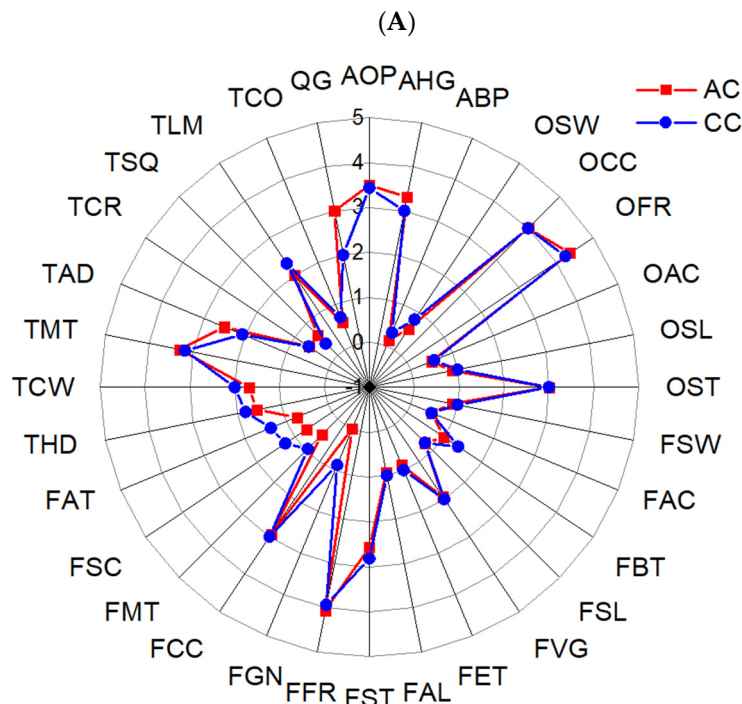


Figure 9. Changes in TPC over 15 days of storage at 4 ± 2 °C for (A) Nevada variety, (B) Pastusa variety, and (C) Diacol Capiro variety, subjected to all treatments: CC: control; AC: citric acid 1.0%; AA: ascorbic acid 1.0%; AE: garlic extract 0.5%.

3.6. Sensory Analysis

Based on all the above results, the Capiro Diacol potato variety and the citric acid immersion treatment were selected for sensory analysis with a trained panel. Figure 10A

shows the descriptors for the D. Capiro CC (control) and AC (treated with citric acid 1%) samples. The descriptors found the following attributes for appearance (A): *opaque* (AOP), *homogeneous color* (AHG), and *presence of browning* (ABP); for odor (O): *sweet* (OSW), *cooked* (OCC), *fresh* (OFR), *acid* (OAC), *saline* (OSL), and *starch* (OST); for flavor (F): *sweet* (FSW), *acid* (FAC), *bitter* (FBT), *saline* (FSL), *vegetable* (FVG), *earthy* (FET), *alkaline* (FAL), *starch* (FST), *fresh* (FFR), *green* (FGN), *cooked* (FCC), *metallic* (FMT), *spicy* (FSC), and *astringent* (FAT); and for texture (T): *hard* (THD), *chewable* (TCW), *moist* (TMT), *sticky* (TAD), *crunchy* (TCR), *squeaking* (TSQ), *lumpy* (TLM), and *coating* (TCO). The figure also shows the *general quality* (QG) for the control (CC) and treated potatoes (AC).



Descriptors for appearance (A): *opaque* (AOP), *homogeneous color* (AHG), and *presence of browning* (ABP); for odor (O): *sweet* (OSW), *cooked* (OCC), *fresh* (OFR), *acid* (OAC), *saline* (OSL), and *starch* (OST); for flavor (F): *sweet* (FSW), *acid* (FAC), *bitter* (FBT), *saline* (FSL), *vegetable* (FVG), *earthy* (FET), *alkaline* (FAL), *starch* (FST), *fresh* (FFR), *green* (FGN), *cooked* (FCC), *metallic* (FMT), *spicy* (FSC), and *astringent* (FAT); for texture (T): *hard* (THD), *chewable* (TCW), *moist* (TMT), *sticky* (TAD), *crunchy* (TCR), *squeaking* (TSQ), *lumpy* (TLM), *coating* (TCO), and *general quality* (QG).

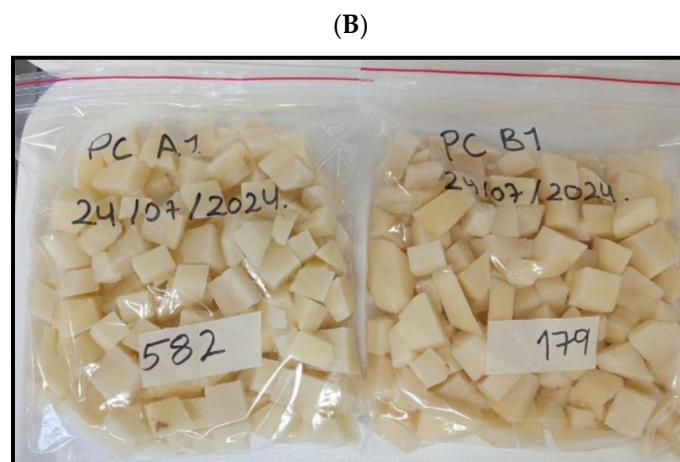


Figure 10. (A) Sensory analysis of Diacol Capiro variety: control treatment (CC) and potatoes subjected to immersion treatment with 1.0% citric acid (AC). (B) Diacol Capiro potato immersed in a 1% citric acid solution (left) and D. Capiro potato immersed in water as a control (right).

The panelists highlighted some aspects of each of the samples. The sensory characteristics of the control (CC) presented different notes associated with starchy, fresh, and cooked flavors, attributed to the cooking process to which the potato was subjected. The potato presented a typical yellow color with slight brownish tones and the presence of opacity. The sensory characterization was due to a number of small, volatile substances, such as methional and some types of pyrazines; the panelists used an effective sensory method that determined the sensory profile as being associated with sweet, earthy, burnt flesh, atypical, moldy, fruity, and “typical” attributes. In addition, the cooking method dictates the type and extent of volatile compounds that are released and perceived through odor attributes [53]. The fresh potato sample presented moist, sticky, and lumpy texture characteristics. The texture of cooked potatoes is associated with various compounds, such as dry solid content, sugars, starch, pectic matter, and proteins, among others. As starch is the predominant substance, texture variations during cooking depend on its behavior and that of the pectic matter. Potatoes subjected to citric acid immersion treatment (AC) showed a homogeneous color appearance and less presence of browning (Figure 10B), as well as no change in odor in relation to cooked notes and starch compared to the control (CC). Similarly, AC presented notes associated with cooked, starchy, and fresh flavors. Since both flavor and odor are processed and interpreted in the same region of the brain, it is not surprising that they present similar attributes [53], like *acid*, *starch*, *saline*, and *cooked*. The sample subjected to AC also reported texture attributes linked to humidity, adhesive, and lumpy qualities. In the AC sample, earthy notes were identified, probably associated with starch granules, since these are agglomerations of hard and tight starch molecules, which produce an earthy sensation when chewed and removed from their cells. Regarding flavor, the astringent descriptor can be associated with the presence of polyphenolic compounds in the potato [53]. Finally, the acid attribute is related firstly to the content of organic acids found in potato tubers, such as ascorbic acid, citric acid, malic acid, and pyrrolidone carboxylic acids [5]. The descriptor *acid* as a flavor attribute was perceived with equal intensity for the AC and CC samples. Since a higher perception was expected for the AC samples, it can be assumed that the cooking process to which the potato was subjected masked the acid flavor, or, the amount added was not sufficient to generate a statistically significant difference compared to the control sample. Therefore, it did not alter the potato’s flavor, odor, or texture characteristics. This is very beneficial because it provides information that the selected treatment was the most appropriate to control browning without affecting the potato, making it a promising treatment to be used as a pretreatment for the development of Minimally Processed potato Products.

4. Conclusions

This study emphasizes the potential of variety selection in preventing unacceptable levels of enzymatic browning in potato and the very noticeable variety-dependent effect of long-term storage under refrigerated conditions. Thus, the degree of browning is variable-dependent. The findings of this study enhance the understanding of which potato varieties from Colombia are suitable for processing as fresh-cut products. Therefore, this study shows that the Diacol Capiro potato is the most suitable variety for producing Minimally Processed Products. Assessing the suitability of a potato variety for processing as a fresh-cut product is the initial step toward achieving a high-quality final product, whether for domestic or industrial use. Although this study used the most widely distributed commercial varieties in the country, future research could focus on expanding the screening to include other varieties and exploring additional technological coadjutants to help postpone the browning process. It is noteworthy that the compound used did not have any sensory impact on the final product, which is essential when it comes to food.

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writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

1. Liu, Y.; Zhang, J.; Zhao, Y.; Bao, Y.; Wu, Z.; Zheng, Y.; Jin, P. Effects of the Combined Treatment of Trans-2-Hexenal, Ascorbic Acid, and Dimethyl Dicarbonate on the Quality in Fresh-Cut Potatoes (*Solanum tuberosum* L.) during Storage. *Foods* **2024**, *13*, 1526. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Gomes, B.A.F.; Alexandre, A.C.S.; de Andrade, G.A.V.; Zanzini, A.P.; de Barros, H.E.A.; Ferraz e Silva, L.M.d.S.; Costa, P.A.; Boas, E.V.d.B.V. Recent Advances in Processing and Preservation of Minimally Processed Fruits and Vegetables: A Review—Part 2: Physical Methods and Global Market Outlook. *Food Chem. Adv.* **2023**, *2*, 100304. [\[CrossRef\]](#)
3. Levaj, B.; Pelaić, Z.; Galić, K.; Kurek, M.; Šćetar, M.; Poljak, M.; Dite Hunjek, D.; Pedisić, S.; Balbino, S.; Čošić, Z.; et al. Maintaining the Quality and Safety of Fresh-Cut Potatoes (*Solanum tuberosum*): Overview of Recent Findings and Approaches. *Agronomy* **2023**, *13*, 2002. [\[CrossRef\]](#)
4. Duarte-Correa, Y.; Vargas-Carmona, M.I.; Vásquez-Restrepo, A.; Ruiz Rosas, I.D.; Pérez Martínez, N. Native Potato (*Solanum phureja*) Powder by Refractance Window Drying: A Promising Way for Potato Processing. *J. Food Process. Eng.* **2021**, *44*, e13819. [\[CrossRef\]](#)
5. Singh, J.; Kaur, L. *Advances in Potato Chemistry and Technology*, 2nd ed.; Elsevier: Palmerston North, New Zealand, 2016.
6. Bobo-García, G.; Arroqui, C.; Merino, G.; Vírveda, P. Antibrowning Compounds for Minimally Processed Potatoes: A Review. *Food Rev. Int.* **2020**, *36*, 529–546. [\[CrossRef\]](#)
7. Singh, B.; Suri, K.; Shevkani, K.; Kaur, A.; Singh, N. Enzymatic Browning of Fruit and Vegetables: A Review. In *Enzymes in Food Technology*; Kuddus, M., Ed.; Springer: Singapore, 2018; pp. 63–78, ISBN 9789811319327.
8. Li, L.; Bai, J.; Wu, M.; Zhao, M.; Wang, R.; Guo, M.; Liu, H.; Liu, T. Studies on Browning Inhibition Technology and Mechanisms of Fresh-Cut Potato. *J. Food Process. Preserv.* **2017**, *41*, e13263. [\[CrossRef\]](#)
9. Venturi, F.; Bartolini, S.; Sanmartin, C.; Orlando, M.; Taglieri, I.; Macaluso, M.; Lucchesini, M.; Trivellini, A.; Zinnai, A.; Mensuali, A. Potato Peels as a Source of Novel Green Extracts Suitable as Antioxidant Additives for Fresh-Cut Fruits. *Appl. Sci.* **2019**, *9*, 2431. [\[CrossRef\]](#)
10. Limbo, S.; Piergiorganni, L. Shelf Life of Minimally Processed Potatoes: Part 1. Effects of High Oxygen Partial Pressures in Combination with Ascorbic and Citric Acids on Enzymatic Browning. *Postharvest Biol. Technol.* **2006**, *39*, 254–264. [\[CrossRef\]](#)
11. Ali, H.M.; El-Gizawy, A.M.; El-Bassiouny, R.E.I.; Saleh, M.A. Browning Inhibition Mechanisms by Cysteine, Ascorbic Acid and Citric Acid, and Identifying PPO-Catechol-Cysteine Reaction Products. *J. Food Sci. Technol.* **2014**, *52*, 3651–3659. [\[CrossRef\]](#)
12. Li, L.; Wu, M.; Zhao, M.; Guo, M.; Liu, H. Enzymatic Properties on Browning of Fresh-Cut Potato. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *397*, 012116. [\[CrossRef\]](#)
13. Mangiapelo, L.; Blasi, F.; Ianni, F.; Barola, C.; Galarini, R.; Abualzulof, G.W.; Sardella, R.; Volpi, C.; Cossignani, L. Optimization of Ultrasound-Assisted Extraction of Chlorogenic Acid from Potato Sprout Waste and Enhancement of the In Vitro Total Antioxidant Capacity. *Antioxidants* **2023**, *12*, 348. [\[CrossRef\]](#)
14. Guan, Y.; Lu, S.; Sun, Y.; Zheng, X.; Wang, R.; Lu, X.; Pang, L.; Cheng, J.; Wang, L. Tea Polyphenols Inhibit the Occurrence of Enzymatic Browning in Fresh-Cut Potatoes by Regulating Phenylpropanoid and ROS Metabolism. *Plants* **2024**, *13*, 125. [\[CrossRef\]](#)
15. Kuijpers, T.F.M.; Van Herk, T.; Vincken, J.P.; Janssen, R.H.; Narh, D.L.; Van Berkel, W.J.H.; Gruppen, H. Potato and Mushroom Polyphenol Oxidase Activities Are Differently Modulated by Natural Plant Extracts. *J. Agric. Food Chem.* **2014**, *62*, 214–221. [\[CrossRef\]](#)
16. Prisacaru, A.E.; Ghinea, C.; Albu, E.; Ursachi, F. Effects of Ginger and Garlic Powders on the Physicochemical and Microbiological Characteristics of Fruit Juices during Storage. *Foods* **2023**, *12*, 1311. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Hamdan, N.; Lee, C.H.; Wong, S.L.; Fauzi, C.E.N.C.A.; Zamri, N.M.A.; Lee, T.H. Prevention of Enzymatic Browning by Natural Extracts and Genome-Editing: A Review on Recent Progress. *Molecules* **2022**, *27*, 1101. [\[CrossRef\]](#)
18. Lim, W.Y.; Cheun, C.F.; Wong, C.W. Inhibition of Enzymatic Browning in Sweet Potato (*Ipomoea batatas* (L.)) with Chemical and Natural Anti-browning Agents. *J. Food Process. Preserv.* **2019**, *43*, e14195. [\[CrossRef\]](#)
19. García-Proccaccini, L.M.; Capezio, S.B. Utilización de Antioxidantes En Papa (*Solanum tuberosum* L.) Minimamente Procesada. *Rev. Latinoam. Papa* **2019**, *23*, 28–38.

20. Suárez, P.A.; Andreu, A.B.; Colman, S.L.; Clausen, A.M.; Feingold, S.E. Pardeamiento Enzimático: Caracterización Fenotípica, Bioquímica y Molecular En Variedades de Papa Nativas de La Argentina. *Rev. Latinoam. Papa* **2016**, *15*, 66–72. [\[CrossRef\]](#)
21. Hasbún, J.; Esquivel, P.; Brenes, A.; Alfaro, I. Propiedades físico-químicas y parámetros de calidad para uso industrial de cuatro variedades de papa. *Agron. Costarric. Rev. Cienc. Agrícolas* **2008**, *33*, 77–89. [\[CrossRef\]](#)
22. González, M.N.; Massa, G.A.; Andersson, M.; Turesson, H.; Olsson, N.; Fält, A.-S.; Storani, L.; Décima Oneto, C.A.; Hofvander, P.; Feingold, S.E. Reduced Enzymatic Browning in Potato Tubers by Specific Editing of a Polyphenol Oxidase Gene via Ribonucleoprotein Complexes Delivery of the CRISPR/Cas9 System. *Front. Plant Sci.* **2020**, *10*, 1649. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Agudelo-Sánchez, S.; Mosquera-Palacios, Y.; David-Úsuga, D.; Cartagena-Montoya, S.; Duarte-Correa, Y. Effect of Processing Methods on the Postharvest Quality of Cape Gooseberry (*Physalis peruviana* L.). *Horticulturae* **2023**, *9*, 1158. [\[CrossRef\]](#)
24. Contreras-Calderón, J.; Calderón-Jaimes, L.; Guerra-Hernández, E.; García-Villanova, B. Antioxidant Capacity, Phenolic Content and Vitamin C in Pulp, Peel and Seed from 24 Exotic Fruits from Colombia. *Food Res. Int.* **2011**, *44*, 2047–2053. [\[CrossRef\]](#)
25. Yanine, T.N.; Nidia, V.C.; Daniel, D.O. Characterization of the Polyphenoloxidase in Three Varieties of Potato (*Solanum tuberosum* L.) Minimally Processed and Its Color Effect @LIMENTECH. *Cienc. Tecnol. Aliment.* **2013**, *11*, 5–12.
26. DiKen, M.E. Inhibitory Effect of Garlic Extracts on Polyphenoloxidase. *Balikesir Üniversitesi Fen Bilim. Enstitüsü Derg.* **2020**, *22*, 240–247. [\[CrossRef\]](#)
27. Duarte-Correa, Y.; Granda-Restrepo, D.; Cortés, M.; Vega-Castro, O. Potato Snacks Added with Active Components: Effects of the Vacuum Impregnation and Drying Processes. *J. Food Sci. Technol.* **2020**, *57*, 1523–1534. [\[CrossRef\]](#)
28. Tsikrika, K.; Tzima, K.; Rai, D.K. Recent Advances in Anti-Browning Methods in Minimally Processed Potatoes—A Review. *J. Food Process. Preserv.* **2022**, *46*, e16298. [\[CrossRef\]](#)
29. Pérez Martínez, B.S.; Ramos Dubón, E.J. Evaluación de Dos Combinaciones de Conservantes y Su Efecto Sobre Un Producto Hortícola de IV Gama. Ph.D. Thesis, Universidad de El Salvador, San Salvador, El Salvador, 2021.
30. ISO 11035; Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC) Norma Técnica Colombiana (NTC) 3932. Análisis Sensorial. Identificación y Selección de Descriptores Para Establecer Un Perfil Sensorial Por Una Aproximación Multidimensional. Instituto. Colombiano de Normas Técnicas y Certificación: Bogotá, Colombia, 1996.
31. Guzmán Valverde, B.; Castañeda, D.; Marino, J.; Chris, D. Efecto de Gelatinización y Retrogradación En Las Características Funcionales y Reológicas de Almidones de Papa (*Solanum tuberosum*) Precocidas. Licentiate Thesis, Universidad Nacional del Santa, Nuevo Chimbote, Peru, 2024. Available online: <https://repositorio.uns.edu.pe/handle/20.500.14278/4420> (accessed on 25 November 2024).
32. Burgos, G.; De Hann, S. *Potencial Nutricional de La Papa Composición Nutricional de La Papa*; Centro Internacional de la Papa: Lima, Peru, 2019.
33. Burgos, G.; Auqui, S.; Amoros, W.; Salas, E.; Bonierbale, M. Ascorbic Acid Concentration of Native Andean Potato Varieties as Affected by Environment, Cooking and Storage. *J. Food Compos. Anal.* **2009**, *22*, 533–538. [\[CrossRef\]](#)
34. Ingallina, C.; Spano, M.; Sobolev, A.P.; Esposito, C.; Santarcangelo, C.; Baldi, A.; Daglia, M.; Mannina, L. Characterization of Local Products for Their Industrial Use: The Case of Italian Potato Cultivars Analyzed by Untargeted and Targeted Methodologies. *Foods* **2020**, *9*, 1216. [\[CrossRef\]](#)
35. Daas Amiour, S.; Hambaba, L. Effect of pH, Temperature and Some Chemicals on Polyphenoloxidase and Peroxidase Activities in Harvested Deglet Nour and Ghars Dates. *Postharvest Biol. Technol.* **2016**, *111*, 77–82. [\[CrossRef\]](#)
36. Morante Carriel, J.; Agnieszka Obrebska, A.; Bru-Martínez, R.; Carranza Patiño, M.; Pico-Saltos, R.; Nieto Rodriguez, E. Distribution, Location and Inhibitors of Polyphenol Oxidases in Fruits and Vegetables Used as Food. *Rev. Cienc. Tecnol. ía* **2014**. Available online: https://www.lareferencia.info/vufind/Record/EC_c953b963d51da31a41cb03afd48b706a (accessed on 25 November 2024).
37. Nemés, A.; Peksa, A. Polyphenols of Coloured-Flesh Potatoes as Native Antioxidants in Stored Fried Snacks. *LWT* **2018**, *97*, 597–602. [\[CrossRef\]](#)
38. Ezekiel, R.; Singh, N.; Sharma, S.; Kaur, A. Beneficial Phytochemicals in Potato—A Review. *Food Res. Int.* **2013**, *50*, 487–496. [\[CrossRef\]](#)
39. Kita, A.; Bakowska-Barczak, A.; Hamouz, K.; Kułakowska, K.; Lisińska, G. The Effect of Frying on Anthocyanin Stability and Antioxidant Activity of Crisps from Red- and Purple-Fleshed Potatoes (*Solanum tuberosum* L.). *J. Food Compos. Anal.* **2013**, *32*, 169–175. [\[CrossRef\]](#)
40. Perla, V.; Holm, D.G.; Jayanty, S.S. Effects of Cooking Methods on Polyphenols, Pigments and Antioxidant Activity in Potato Tubers. *LWT Food Sci. Technol.* **2012**, *45*, 161–171. [\[CrossRef\]](#)
41. Cantos, E.; Tudela, J.A.; Gil, M.I.; Espin, J.C. Phenolic compounds and related enzymes are not rate-limiting in browning development of fresh-cut potatoes. *J. Agric. Food Chem.* **2002**, *50*, 3015–3023. [\[CrossRef\]](#)
42. Duarte-Correa, Y.; Vega-Castro, O.; López-Barón, N.; Singh, J. Fortifying Compounds Reduce Starch Hydrolysis of Potato Chips during Gastro-small Intestinal Digestion in Vitro. *Starch* **2021**, *73*, 2000196. [\[CrossRef\]](#)
43. Simkova, D.; Lachman, J.; Hamouz, K.; Vokal, B. Effect of Cultivar, Location and Year on Total Starch, Amylose, Phosphorus Content and Starch Grain Size of High Starch Potato Cultivars for Food and Industrial Processing. *Food Chem.* **2013**, *141*, 3872–3880. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Zhao, Y.; Bilbao-Sainz, C.; Wood, D.; Chiou, B.-S.; Powell-Palm, M.J.; Chen, L.; McHugh, T.; Rubinsky, B. Effects of Isochoric Freezing Conditions on Cut Potato Quality. *Foods* **2021**, *10*, 974. [\[CrossRef\]](#)

45. Yapi, J.C.; Gnangui, S.N.; Dabonné, S.; Kouamé, L.P. Inhibitory Effect of Onions and Garlic Extract on the Enzymatic Browning of an Edible Yam (*Dioscorea Cayenensis*-Rotundata Cv. Kponan) Cultivated in Côte d'Ivoire. *Int. J. Curr. Res. Acad. Rev.* **2015**, *3*, 219–231.
46. Bradshaw, M.P.; Prenzler, P.D.; Scollary, G.R. Ascorbic Acid-Induced Browning of (+)-Catechin in a Model Wine System. *J. Agric. Food Chem.* **2001**, *49*, 934–939. [[CrossRef](#)]
47. Dong, T.; Cao, Y.; Jiang, C.-Z.; Li, G.; Liu, P.; Liu, S.; Wang, Q. Cysteine Protease Inhibitors Reduce Enzymatic Browning of Potato by Lowering the Accumulation of Free Amino Acids. *J. Agric. Food Chem.* **2020**, *68*, 2467–2476. [[CrossRef](#)]
48. Moon, K.M.; Kwon, E.-B.; Lee, B.; Kim, C.Y. Recent Trends in Controlling the Enzymatic Browning of Fruit and Vegetable Products. *Molecules* **2020**, *25*, 2754. [[CrossRef](#)]
49. Tsouvaltzis, P.; Brecht, J.K. Inhibition of Enzymatic Browning of Fresh-Cut Potato by Immersion in Citric Acid Is Not Solely Due to pH Reduction of the Solution: Immersion of Fresh-Cut Potato in Citric Acid. *J. Food Process. Preserv.* **2017**, *41*, e12829. [[CrossRef](#)]
50. Sidhu, R.S.; Hunt, I.; Bound, S.A.; Swarts, N.D. Crop Load, Fruit Quality and Mineral Nutrition as Predictors of Fruit Softening and Internal Flesh Browning in Modern Firm Fleshed Apple Cultivars. *Sci. Hortic.* **2024**, *330*, 113035. [[CrossRef](#)]
51. Tang, R.; Zhou, Y.; Chen, Z.; Wang, L.; Lai, Y.; Chang, S.K.; Wang, Y.; Qu, H.; Jiang, Y.; Huang, H. Regulation of Browning and Senescence of Litchi Fruit Mediated by Phenolics and Energy Status: A Postharvest Comparison on Three Different Cultivars. *Postharvest Biol. Technol.* **2020**, *168*, 111280. [[CrossRef](#)]
52. Fei, M.L.; Tong, L.I.; Wei, L.I.; De Yang, L. Changes in antioxidant capacity, levels of soluble sugar, total polyphenol, organosulfur compound and constituents in garlic clove during storage. *Ind. Crops Prod.* **2015**, *69*, 137–142. [[CrossRef](#)]
53. Duarte-Correa, Y.; Díaz-Osorio, A.; Osorio-Arias, J.; Sobral, P.J.A.; Vega-Castro, O. Development of Fortified Low-Fat Potato Chips through Vacuum Impregnation and Microwave Vacuum Drying. *Innov. Food Sci. Emerg. Technol.* **2020**, *64*, 102437. [[CrossRef](#)]

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