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ORIGINAL ARTICLE

Combined Effects of Ultra-High-Pressure Homogenization and Enzyme Treatments on the Quality Properties of Juice From Apple Industrial By-Products

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ABSTRACT

The objective of this study was to investigate the influence of ultra-high pressure homogenization [UHPH, 0 MPa (Control without UHPH), 100, and 150 MPa] and different enzyme treatments (non-enzyme, pectinase and cellulase) on some quality and color changes of fruit juices produced from dried apple pomace powder (DAPP). DAPP was a valuable waste product due to its high total phenolic content (198.42 ± 2.60 mg GAE/100 g dw) as well as low moisture (2.78 ± 0.17%) and pH (3.20 ± 0.03). The pH, total soluble solids (TSS), color, total color difference (ΔE), and National Bureau of Standards (NBS) parameters of fruit juices (DAPPJ) produced from DAPP were affected by both enzyme ($p < 0.01$) and UHPH treatments ($p < 0.01$). Enzyme and UHPH treatments increased the TSS value ($p < 0.05$). Pectinase treatment of DAPPJ resulted in lower pH values and color coordinates (L^*, a^*, and b^*) compared to cellulase and non-enzyme groups ($p < 0.05$). Regardless of enzyme treatment, UHPH processing increased lightness and yellowness, while decreasing redness in DAPPJ. The combination of pectinase enzyme and 100 MPa UHPH offered a 'distinct' color difference with the lowest ΔE, while ΔE was 'very distinct' in all treatment groups processed with 150 MPa UHPH ($p < 0.05$). The color difference based on NBS classification was "noticeable" for enzyme treatments and "appreciable" for UHPH processing. Considering a lighter yellowish and less reddish fruit juice for consumer acceptance, the combination of cellulase enzyme and 150 MPa UHPH can be recommended for industrial applications of DAPPJ. On the other hand, to minimize the visible color difference, a combination of pectinase enzyme and 100 MPa UHPH is a more suitable option for DAPPJ production.

1 | Introduction

Recently, within the scope of trends toward efficient use of natural resources, fruit and vegetable processing industry wastes stand out as a remarkable issue. Because evaluating industrial wastes directly as waste without carrying out studies to transform them into value-added products causes a significant loss of biomass in the environment. Especially, by-products from the fruit processing industry constitute a significant waste potential, and their disposal is often problematic (Erdoğan and Demirci 2015; Costa et al. 2022).

Apple is a fruit with high amounts of cellulose and pectin in its structure and high dietary fiber content (Masoodi et al. 2002). The pomace is obtained as waste during the industrial processing of apples; it is a large waste product that mostly accumulates during the processing of apples into fruit juice. Apple pomace is a valuable by-product that constitutes

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25%–35% of fruit juice industry wastes, and contains 11.7% pectin, 24.4% hemicellulose, 43.6% cellulose and 20.4% lignin in its composition. It is known that during the industrial processing of apples, the important phytochemicals and important components it contains pass into the fruit pomace more than the fruit juice (Sülük et al. 2018; Costa et al. 2022). Globally, an estimated 4 million tons of apple pomace containing valuable nutrients are produced annually, and this figure is expected to increase in the future (Costa et al. 2022; Gołębiewska et al. 2022). The waste apple pomace is largely biodegradable and organic, and also poses a serious problem for the environment (Vendruscolo et al. 2008). The wastes are important sources of sugars, minerals, organic acids, food fiber, and phenolics with antimutagenic, cardioprotective, antibacterial, and antiviral effects. Despite being a rich source, industrial apple wastes, like other fruit and vegetable industry wastes, are also generally evaluated as animal feed (Erdoğan and Demirci 2015).

During juice processing, the breakdown of colloidal structures into small molecules is important for the production of clear and stable juice. For this reason, while some methods can be used in technological terms, the most commonly used method is enzyme applications (Sharma et al. 2017; de Souza and Kawaguti 2021). Selective enzymes such as pectinases, hemicellulases, and cellulases are used for hydrolytic degradation of relevant cell wall components. Breakdown reactions that take a long time without enzymes can take place within 3–6 h with the use of enzymes. The most important enzyme group in the sector is pectinases, and these enzymes are responsible for breaking down the complex pectin structure in the fruit peel and therefore passing into the pulp during processing. For pectinase enzymes, pectin lyase and polygalacturonase activity are important (Bhat 2000; Yuan et al. 2011). On the other hand, cellulolytic enzymes hydrolyse the beta-1,4-glucosidic bonds of cellulose, a polysaccharide composed of glucose (de Souza and Kawaguti 2021). Juice yield and juice quality can be increased by using enzymes such as cellulases and pectinases alone or in combination (Sharma et al. 2017). In the fruit juice industry, enzyme applications have advantages such as rapid maceration, depectinization, extraction efficiency, maximum pressing capacity, and prevention of turbidity. Enzymatic hydrolysis of cell walls can increase the reducing sugar, water-soluble solids content, and titratable acidity of the products. The enzymatic degradation process of biomaterials varies depending on the type of enzyme, incubation temperature and time, pH, enzyme concentration, and the use of different enzyme combinations (Akyıldız and Uçan 2012; de Souza and Kawaguti 2021).

In apple juice processing, the optimum pH value is 3–5 and the temperature is in the range of 40°C–60°C (Yuan et al. 2011; Detoni et al. 2025), so the enzymes used in production must be compatible with these conditions. In the present study, the enzymes used in apple juice processing were selected based on the criteria of temperature tolerance and adaptation to pH conditions (Zhu et al. 2024; Detoni et al. 2025), positive effect on phenolic content and antioxidant activity (Oszmiański et al. 2009, 2011; Bautista-Expósito et al. 2022), fast and effective depectinization, easy filtration, improvement of viscosity and clarity, low galacturonic acid production, clear dosage instructions, widespread use in the industry and proven performance (Zhu et al. 2024; Novozymes 2025a, 2025b). Ultimase BWL 40 is a commercial cellulase enzyme that provides basic enzyme activity by hydrolyzing (1,4)-beta-D-glucosidic bonds in cellulose and other beta-D-glucans. Among commercial pectinases, Pectinex XXL provides basic enzyme activity through pectin lyase, while also exhibiting polygalacturonase activity. On the other hand, Pectinex XXL (*Aspergillus niger*, *Aspergillus aculeatus*) and Ultimase BWL 40 (*Trichoderma reesei*) are reliable because they are obtained from food-grade microbial sources (Sharma et al. 2017; Novozymes 2025a, 2025b).

Ultra-high-pressure homogenization (UHPH) is a non-thermal technology that has been widely studied to partially or completely replace traditional thermal preservation processes used in the food industry to minimize undesirable changes in the sensory and nutritional properties of liquid products. The main effect of UHPH is to reduce the size of particles, thus preserving bioactive compounds, inactivating microorganisms, and preserving sensory properties while affecting the physical stability of the products (Augusto et al. 2018; Lima and Rosenthal 2023). The UHPH process can be used in fruit juice technology for its important advantages, such as reducing pulp precipitation, increasing physical stability, and improving physical properties (Augusto et al. 2018; Turan et al. 2024; Aksu et al. 2025).

The use of pectinase and cellulase enzymes, alone or in combination, in fruit juice production has been evaluated in previous studies (Sharma et al. 2017; Ozyilmaz and Gunay 2023; Detoni et al. 2025). Similarly, the combined use of enzyme treatment and non-thermal technologies in fruit juice processing is also under consideration (Schilling et al. 2008; la De Peña-Armada et al. 2020; Klavins et al. 2022). However, to our knowledge, there are no studies evaluating the effects of the combined use of commercial pectinase and cellulase enzymes with UHPH in fruit juice production from apple industrial by-products. The aim of this study was to investigate the effects of enzyme (non-enzyme, pectinase, and cellulase) and UHPH [0 MPa (Control without UHPH), 100 MPa and 150 MPa] treatments on some quality and color characteristics of fruit juices produced from apple pomace powder, a valuable apple processing waste.

2 | Materials and Methods

2.1 | Production of Dried Apple Pomace Powder (DAPP)

The raw material used in the study was obtained from a special fruit processing factory as a by-product of fresh apple pulp processing. Apple by-products include seeds, stems, peel, and some pulp of the fruit. Fresh apple pulp waste (apple pomace) was dried for approximately 30 min in a drum dryer system at 250°C–300°C. The samples were kept in this system where hot air was spread with aspirators until the product moisture level reached below 5%. Then, the dried products were ground to 130–150 μm in a hammer mill (Retsch mill/SM 300) system. In this way, DAPP production from dried apple pulp waste was carried out (Figure 1).

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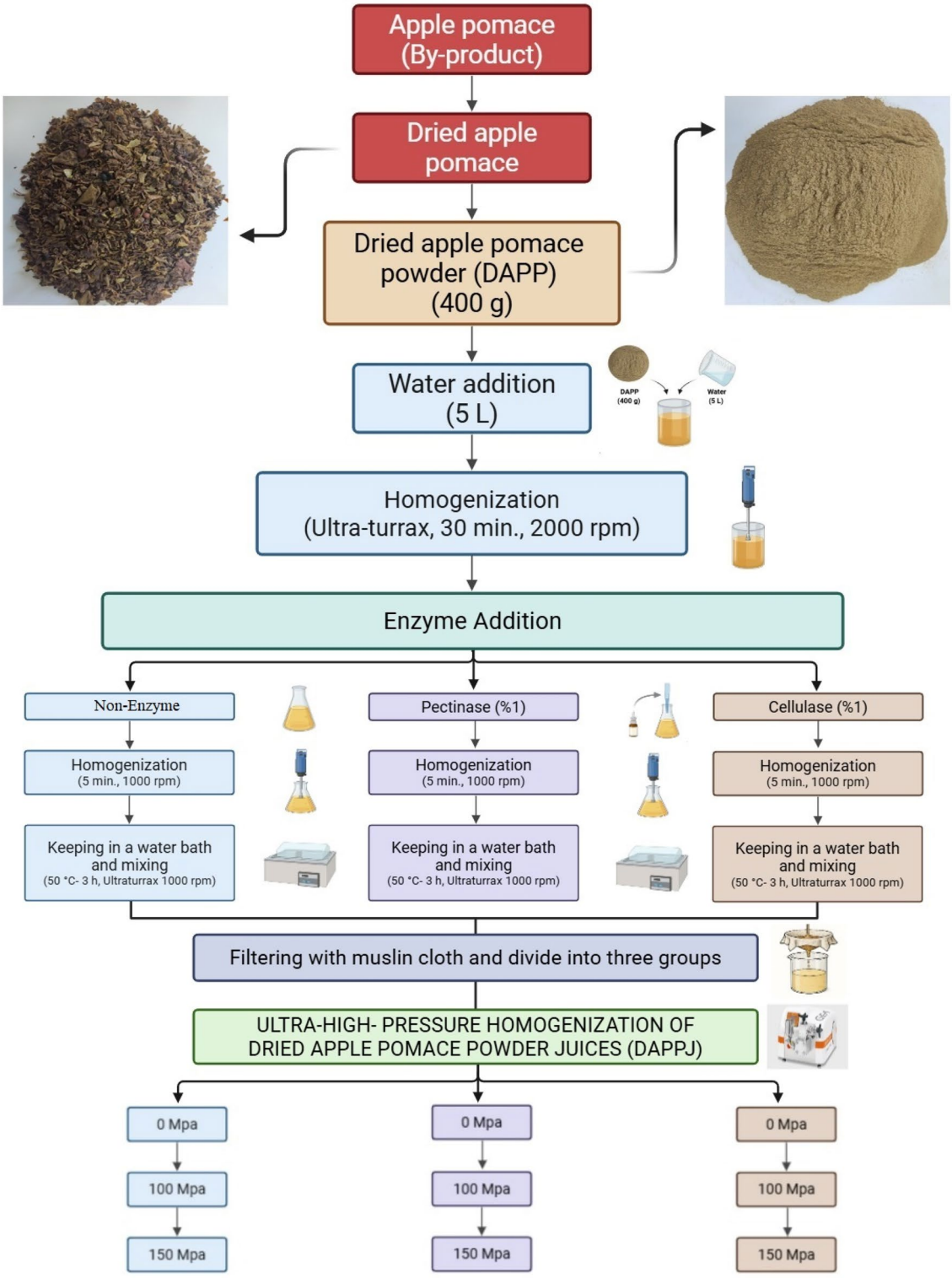

FIGURE 1 | Production stages of dried apple pomace powder juice (DAPPJ) by enzyme and UHPH treatments.

2.2 | Preparation of Juice From DAPP and Enzyme Treatments

The production stages of dried apple pomace powder juice (DAPPJ) obtained from DAPP and the enzymes and UHPH treatments applied to fruit juice are shown in Figure 1. Briefly, 400 g of DAPP was taken, and 5 L of water was added to it. Then, the mixture was homogenized with a mixer (Ultra Turrax) at 2000 rpm for 30 min at room temperature (Homogenized DAPPJ stage). After this process, enzyme addition (1%) was performed. Industrial pectinase (10,000 PECTU/ml, Pectinex XXL, Bagsværd, Denmark) and cellulase (1200 cellulase IU/g, Ultimase BWL 40, Bagsværd, Denmark) enzymes were used. After enzyme addition, mixing was applied for 5 min at room temperature and then kept in a 50°C water bath for 3 h (Enzyme incubation stage). During this process,

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it was continuously mixed with an Ultra Turrax at 1000 rpm. Then, samples were filtered with muslin cloth and divided into three groups and UHPH treatments [0 MPa (Control without UHPH), 100 MPa, and 150 MPa] were performed. The same procedures were applied to the group (Non-Enzyme) without enzyme treatment.

$$\Delta E = \sqrt{\left(CIEL^*_{treatment} - CIEL^*_{control}\right)^2 + \left(CIEa^*_{treatment} - CIEa^*_{control}\right)^2 + \left(CIEb^*_{treatment} - CIEb^*_{control}\right)^2} \quad (3)$$

2.3 | UHPH Processing

UHPH treatments were performed at pressures of 100 and 150 MPa, an inlet temperature of 4°C, an outlet temperature range of 34.5°C–36.2°C, and a flow rate of 9 L/s using an ultra-high pressure homogenizer (GEA Homogenizer Panda PLUS 2000, Parma, Italy). The juice was passed through the HPH system in a single cycle at the set pressure. Since pressure application increases the product temperature, cooling was done in an ice bath, and then analyses were carried out.

2.4 | DAPP Analysis

Moisture content was determined using a moisture analyzer (Radwag MAC 50, Poland). For pH measurement, 1 g of DAPP was homogenized in 50 mL of distiled water for 1 min using a homogenizer (IKA T25 Ultra-Turrax, Germany). The homogenate was then filtered and the pH value of the filtrate was measured using a digital pH meter (Mettler Toledo S210, Switzerland). Instrumental color coordinates of DAPP were measured using a CR-410 chromo meter (Konica Minolta, Osaka, Japan) with a D65 illuminant, 50 mm illumination area, and 2° observer conditions. As a pretreatment for antioxidant capacity analyses, 0.5 g of DAPP was mixed with 10 mL of methanol-distilled water mixture (80:20 v/v) and extraction was carried out for 2 h at room temperature using a mini-rotator (Biosan RS-24, Riga, Latvia). Total phenolic content was determined as mg gallic acid equivalent (GAE)/100 g dry weight (dw) following the Folin–Ciocalteu procedure (Singleton et al. 1999). DPPH radical scavenging activity, ABTS radical scavenging activity, and Ferric reducing antioxidant power (FRAP) were evaluated using the tests developed by Brand-Williams et al. (1995), Re et al. (1999) and Benzie and Strain (1996), respectively. The results of the three in vitro antioxidant activity tests were calculated as mmol trolox equivalents (TE)/g dw.

2.5 | DAPPJ Analysis

2.5.1 | Instrumental Color Coordinates

The color coordinates of DAPPJ samples according to the CIELab color space were measured using a colorimeter (CR-400, Konica Minolta, Japan). CIE L^* (lightness/darkness), CIE a^* (redness/greenness), and CIE b^* (yellowness/blueness) coordinates were determined in the measurements. Chroma (C^*), hue angle ($h°$) and total color difference (ΔE) parameters of samples were calculated from L^*, a^*, and b^* coordinates according to Equations (1–3), respectively. Then, using ΔE parameter, National Bureau of Standards (NBS) parameters were calculated according to Equation (4).

$$C* = \sqrt{(CIEa^*)^2 + (CIEb^*)^2} \quad (1)$$

$$h^\circ = \arctan\left(b^* / a^*\right) \quad (2)$$

$$\mathrm{NBS}^{\pm} = \Delta E \times 0.92 \quad (4)$$

$^{\pm}$where [0–0.5 (trace), 0.5–1.5 (slight), 1.5–3.0 (noticeable), 3.0–6.0 (appreciable), 6.0–12.0 (much), ≥ 12.0 (very much)].

2.5.2 | Total Soluble Solids (TSS) Values

The TSS values of DAPPJ samples with enzyme and UHPH treatment were measured using a digital refractometer (Hanna HI 96801, USA) at a constant temperature of 20°C, made in triplicate, and the results were expressed as °Brix.

2.5.3 | pH Values

The pH values of the DAPPJ samples were determined using a benchtop pH meter (Hanna Instruments, USA) at 25°C. Before use, the pH meter was calibrated with three different buffer solutions (pH: 4.0, 7.0, and 10.0).

2.5.4 | Statistical Analysis

The experiment was conducted using a randomized factorial design, considering enzyme treatments (Non-enzyme, Pectinase, Cellulase) and processing stages [Homogenized DAPPJ; Enzyme incubation, 0 MPa UHPH (Control without UHPH), 100 MPa UHPH, and 150 MPa UHPH]. All analytical measurements were performed in triplicate. Data were analyzed using mixed model ANOVA (General Linear Model), with factors (enzyme treatments and processing stages) and their interactions as fixed effects, and replication as random effects. Statistical analysis was performed using the SPSS package program (SPSS 23.0). The differences were verified by Duncan Multiple Comparison Test (within the 95% confidence interval, $p < 0.05$).

3 | Results and Discussion

3.1 | Characteristics of DAPP

Table 1 presents the characteristics of DAPP. The DAPP had a low moisture content (2.78 ±0.17%) and an acidic character (pH 3.20 ±0.03; TA: 0.46 ±0.02%), which was comparable to the results of previous studies (Büker et al. 2021; Salari et al. 2024). The L^*, a^* and b^* coordinates of DAPP 43.45 ±0.33, 4.64 ±0.05 and 13.99 ±0.12, respectively. The chroma (C^*) parameter is considered the quantitative quality of colourfulness and indicates the degree of

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TABLE 1 | Characteristics of dried apple pomace powder (DAPP).

Properties	DAPP
Moisture (%)	2.78 ± 0.17
pH	3.20 ± 0.03
Titratable acidity (TA, % malic acid)	0.46 ± 0.02
Lightness/darkness (L^*)	43.45 ± 0.33
Redness/greenness (a^*)	4.64 ± 0.05
Yellowness/blueness (b^*)	13.99 ± 0.12
Chroma (C^*)	14.74 ± 0.12
Hue angle ($h°$)	71.64 ± 0.18
Total phenolic content (mg GAE/100 g dw)	198.42 ± 2.60
DPPH radical scavenging activity (mmol TE/g dw)	0.54 ± 0.01
ABTS radical scavenging activity (mmol TE/g dw)	0.88 ± 0.07
Ferric reducing antioxidant power (FRAP, mmol TE/g dw)	0.25 ± 0.01

Note: All values are expressed as mean ± standard deviation of three replicates ($n = 3$).
Abbreviation: dw, dry weight.

TABLE 2 | Mean pH and total soluble solids (TSS) values of DAPPJ samples treated with different enzyme types and ultra-high pressure homogenization (UHPH) treatments.

	pH	TSS (°Brix)
Enzyme treatment (ET)		
Non-enzyme	3.93 ± 0.11a	2.05 ± 0.11b
Pectinase	3.69 ± 0.20c	2.68 ± 0.35a
Cellulase	3.88 ± 0.12b	2.68 ± 0.39a
SEM	0.002	0.017
p	**	**
Processing stage (PS)		
Homogenized DAPPJ	4.11 ± 0.05a	2.13 ± 0.11d
Enzyme incubation	3.74 ± 0.13d	2.29 ± 0.24c
0 MPa UHPH (control)	3.77 ± 0.13c	2.65 ± 0.45ab
100 MPa UHPH	3.77 ± 0.13c	2.59 ± 0.42b
150 MPa UHPH	3.78 ± 0.13b	2.69 ± 0.49a
SEM	0.003	0.022
p	**	**
Interactions		
ET × PS	**	**

Note: [a–c]: Means of the same column and in the same section having the same letters are not significantly different at $p > 0.05$ (Duncan's test) between the means of enzyme treatments. [a–d]: Means of the same column and in the same section having the same letters are not significantly different at $p > 0.05$ (Duncan's test) between the means of processing stage.
Abbreviation: ± standard deviations.

color saturation. Higher C^* parameters result in higher color intensity perceived by humans. The hue angle ($h°$) varies from 0° to 360°, where 0/360° represents maximum redness, 90° represents maximum yellowness, 180° represents maximum greenness, and 270° represents maximum blueness (Bhat et al. 2023). According to the color parameters, the DAPP is perceived as light orange-yellow or yellowish-orange with moderate saturation.

The total phenolic content (198.42 ± 2.60 mg GAE 100 g^{-1} dw) of DAPP was consistent with some results in the literature (Antonic et al. 2020; Büker et al. 2021; Salari et al. 2024), although higher total phenolic content was also found in apple pomaces dried by different methods (Yan and Kerr 2013; Sabet Ghadam et al. 2023; Bhat et al. 2023). This may be due to differences in apple cultivar, growing and harvesting conditions, processing methods, juice production technique, clarification, extraction and storage conditions (Gorjanović et al. 2020; Büker et al. 2021). The antioxidant capacity of DAPP was evaluated by DPPH, ABTS and FRAP assays and the values were 0.54 ± 0.01, 0.88 ± 0.07 and 0.25 ± 0.01 mmol TE/g, respectively (Table 1). Antioxidant activity values were similar to those reported by Grispoldi et al. (2022) for dried apple pomace. Gorjanović et al. (2020) determined that the antioxidant capacity of apple pomace was strongly correlated with the total phenolic and flavonoid contents. Apple pomace consists of 95% peel and pulp, 2%–4% seeds and 1% stems, and all these parts contain a large number of phytochemicals. Phenolic acids are abundant in the pulp and quercetin glycosides in the peel (Kauser et al. 2024). Phenolic compounds (especially quercetin, chlorogenic acid, phlorizin, procyanidins, protocatechuic acid) are thought to be primarily responsible for the antioxidant capacity of apple pomace (Lu and Foo 2000; Gorjanović et al. 2020; Bhat et al. 2023). Lu and Foo (2000) reported that apple pomace polyphenols exhibited better DPPH scavenging (2–3 times) and superoxide scavenging (10–30 times) activities than vitamins C or E. Accordingly, apple pomace powder has remarkable potential to enhance the nutritional value and fortification the functional properties of various food products.

The moisture content of apple pomace is generally in the range of 70%–85%. Therefore, it is highly sensitive to microbial spoilage and oxidation of polyphenols. Cooling and freezing methods to extend storage time are neither economical nor practical due to the energy and space required. A possible solution to overcome this problem is to dry the apple pomace immediately after production, reducing its moisture content to below 10% (Jung et al. 2015; Antonic et al. 2020). Using different drying techniques, the moisture content of apple pomace can be reduced to as low as 2% (Antonic et al. 2020; Bhat et al. 2023). Drying provides longer storage time, elimination of unpleasant odors, and lower transportation and storage costs (Jung et al. 2015; Bhat et al. 2023). Different drying methods (hot air drying, spray drying, microwave drying, vacuum drying, freeze drying, etc.) are used in the food industry. Freeze-drying and vacuum drying techniques offer the best quality preservation but have the highest costs (Yan and Kerr 2013; Jung et al. 2015; Bhat et al. 2023). In the present study, DAPP was produced using a drum dryer that provides easy, fast, and low-energy production. The available findings indicate that DAPP is a valuable waste product with promising potential for use as a functional food ingredient.

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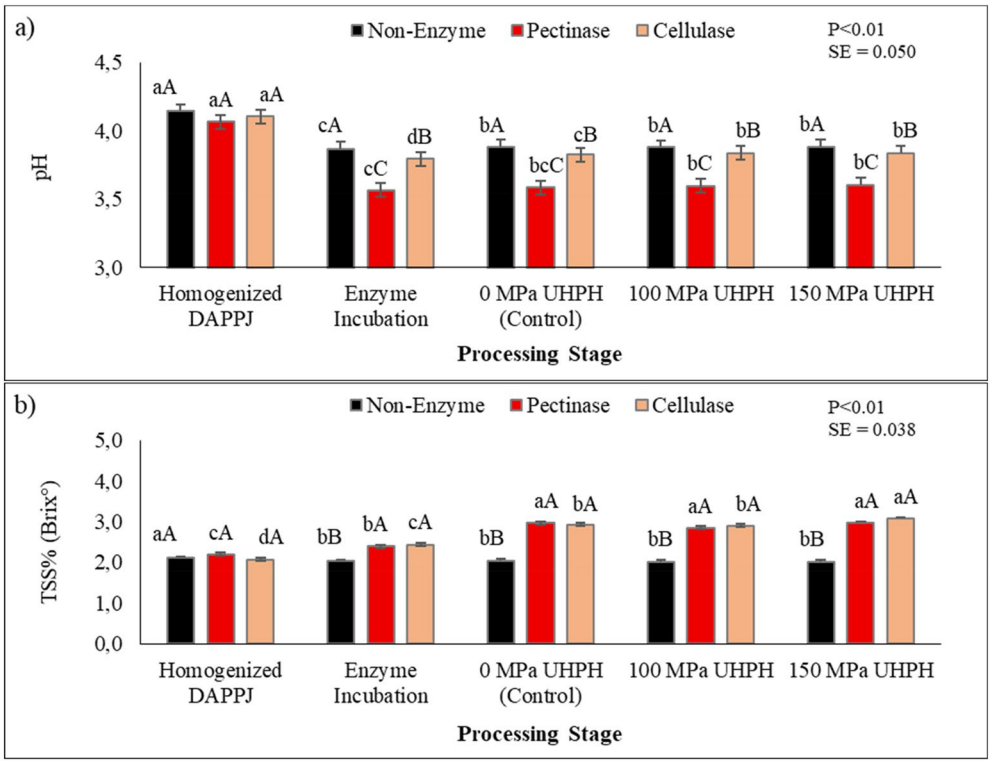

FIGURE 2 | Effect of enzyme treatment × processing stage interaction on the pH (a) and TSS (°Brix) (b) value of dried apple pomace powder juice (DAPPJ). Lowercase and uppercase letters in bar graphs represent significant differences between processing stages per each enzyme treatment and between enzymes per each processing stage, respectively ($p < 0.05$, Duncan test).

3.2 | pH and TSS of DAPPJ Samples

The pH and TSS analyses results of DAPPJ samples treated with different enzyme types and UHPH levels are given in Table 2. Depending on the enzyme type, a statistically significant ($p < 0.01$) change in the pH value of DAPPJ samples was observed. The use of enzyme decreased the pH value compared to the non-enzyme group, and pectinase was more effective in decreasing the pH than cellulase ($p < 0.05$). The effect of the enzyme on this decrease is important, and this effect varies depending on incubation time and temperature, pH, enzyme concentration, agitation, and the use of different enzyme combinations (Sharma et al. 2017; Detoni et al. 2025). The breakdown of the cell wall by enzymes results in the release of various nutrients as products, and these components increase the titratable acidity (Zou et al. 2024). Both production stages ($p < 0.01$) and enzyme treatment × production stages interaction ($p < 0.01$) had very significant effects on pH value (Table 2). The highest (4.11 ± 0.05) and lowest (3.74 ± 0.13) mean pH values were observed at the initial (homogenized DAPPJ) and enzyme incubation stages, respectively ($p < 0.05$). In the present study, a three-hour incubation period resulted in a decrease in pH. Similarly, Sharma et al. (2017) reported that the activity of the enzyme added to the fruit juices was dependent on the incubation time, and that the decrease in pH occurred in the second and third incubation hours rather than the first hour. As clearly seen in Figure 2a, the greatest decrease (from 4.07 to 3.57) in pH of homogenized DAPPJ samples during enzyme incubation occurred with pectinase treatment. This may be related to the release of carboxyl groups such as galacturonic acid and certain acidic substances during the breakdown of pectin (Ninga et al. 2021; Abdulmumini et al. 2025). On the other hand, pH values of the samples increased after UHPH treatment compared to the enzyme incubation stage, with a significant increase at 100 and 150 MPa UHPH levels (Figure 2a). These findings were similar to previous studies reporting similar increases in the pH values of fruit juices with UHPH treatment (Wellala et al. 2020; Sauceda-Gálvez et al. 2021; Turan et al. 2024). The increase in pH of UHPH-treated fruit juices can be attributed to the breakdown of pectin and proteins (Wellala et al. 2020; Aksu et al. 2025), the extraction of alkali-forming compounds from residual particles (Kruszewski et al. 2023), and the release of cellular components (Zhou et al. 2017). Furthermore, while CO_2 solubility increases under high pressure, the removal of CO_2 from the juice after depressurisation may have altered the carbonic acid balance, leading to an increase in pH (Oulé et al. 2013). In contrast to our findings, Suárez-Jacobo et al. (2011) and Marszałek et al. (2023) found that UHPH (100–300 MPa) treatment did not significantly affect the pH of clear apple juices. Aksu et al. (2025) stated that the effect of the UHPH process on pH may vary depending on the raw material matrix from which the juice is produced, the production conditions and the applied process.

In the present study, significant ($p < 0.01$) effects of enzyme treatment, processing stage, and enzyme treatment × processing stage interaction on TSS value were determined (Table 2). The mean TSS in the non-enzyme group (2.05 ± 0.11 °Brix) increased with enzyme treatment ($p < 0.05$), but no significant difference was detected between pectinase and cellulase enzymes ($p > 0.05$). In other words, both pectinase and cellulase enzymes had a similar effect on TSS. Enzymes play a crucial role in fruit juice production, due to the enzymatic

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degradation of cell walls increases the yield by liberating nutrients from the cells, which leads to elevated levels of polyphenols, total soluble solids, sugars, titratable acidity and galacturonic acid (Zou et al. 2024). The lowest mean TSS values were measured in homogenized DAPPJ, where no enzyme or UHPH treatment were applied. Although mean TSS values increased slightly during the enzyme incubation stage, the highest values were found after UHPH treatment ($p < 0.05$). In other words, both enzyme and UHPH treatments increased TSS values (Table 2). In juices treated with different combinations of various enzymes, the TSS content increases due to higher tissue breakdown and release of more compounds such as sugars (Sharma et al. 2017).

As shown in Figure 2b, all treatment groups had similar ($p > 0.05$) TSS in homogenized DAPPJ. However, from the enzyme incubation onwards, higher ($p < 0.05$) TSS values were observed in the samples treated with pectinase and cellulase than the non-enzyme group. Pectinases break down pectin into smaller molecules (oligogalacturonates), and the release of sugars contributes to an increase in TSS content (Ninga et al. 2021). Regarding cellulolytic enzymes, endoglucanase and exoglucanase work synergistically to convert cellulose into small cello-oligosaccharides, which are then hydrolyzed by beta-glucosidase into simple sugars or glucose. Cellulases also release intracellular soluble components (de Souza and Kawaguti 2021).

On the other hand, there was no difference ($p > 0.05$) in TSS content between samples treated with pectinase and cellulase in all processing stages. In enzyme-treated samples, UHPH processing increased TSS, with the highest ($p < 0.05$) contents observed in samples treated with 150 MPa UHPH (Figure 2b). These results showed that macromolecules whose structures were disrupted by enzymes can be further broken down with UHPH treatment. In other words, the combined application of enzyme and UHPH processing to fruit juices produced from pulp waste was more effective than enzyme treatment alone in increasing TSS content. The effect of UHPH may vary depending on the properties of the raw material (root, leaf, fruit, seed, etc.) used in juices produced from fruits and vegetables and the structural properties of the sugars and other macromolecules it contains and the applied process. In this context, studies generally showed that UHPH increased the amount of TSS (Liu et al. 2021; Yan et al. 2022; Karacam et al. 2015; Aksu et al. 2025). However, there are studies that decrease (Turan et al. 2024) and/or do not change TSS with UHPH processing (Benjamin and Gamrasni 2020; Wellala et al. 2020; Marszałek et al. 2023).

3.3 | Instrumental Color Coordinates of DAPPJ Samples

Instrumental color coordinates (L^*, a^*, and b^*) of DAPPJ samples were effected by enzyme treatment ($p < 0.01$) and processing stage ($p < 0.01$). Considering the L^*, a^*, and b^* color coordinates, the pectinase enzyme caused a significant decrease ($p < 0.05$) compared to the non-enzyme group, while no significant difference was found between the cellulase and non-enzyme treatment groups ($p > 0.05$) (Table 3, Figure 3). Enzyme incubation decreased ($p < 0.05$) the color coordinates (L^*, a^*, and b^*) of homogenized DAPPJ. Similarly, previous studies reported that different commercial enzyme treatments reduced color parameters in apple, blueberry, artichoke, and broccoli by-product extracts or juices (Oszmiański et al. 2009; Siddiq et al. 2018; Ayuso et al. 2024). On the other hand, groups treated with 100 and 150 MPa UHPH had higher ($p < 0.05$) L^* and b^* color coordinates compared to the 0 MPa UHPH treatment (Table 3). The increase in lightness can be attributed to greater light diffraction resulting from decreased particle size (Velázquez-Estrada et al. 2019). As shown in Figure 3a,c, which present significant ($p < 0.01$) enzyme treatment × processing stage interactions for L^* and b^* coordinates, the application of muslin cloth filtration (Figure 1) after enzyme incubation reduced macromolecules not broken down by enzymes and made the fruit juices more homogeneous. Regardless of enzyme treatment, all samples treated with UHPH had higher ($p < 0.05$) lightness and yellowness compared to those without UHPH (Figure 3a,c).

Contrary to L^* and b^* coordinates, the redness (a^* coordinate) decreased during the processing stage; the highest (9.25 ± 0.20) and lowest (-0.12 ± 0.21) average values were recorded in homogenized DAPPJ and the 150 MPa UHPH group, respectively ($p < 0.05$) (Table 3). According to the two-way interaction (Figure 3b) of enzyme treatment and processing stages on redness, there was no difference ($p > 0.05$) between treatments in terms of these values at the initial stage (homogenized DAPPJ). On the other hand, samples treated with cellulase enzyme at all processing stages had a similar ($p > 0.05$) redness to the non-enzyme group without enzyme treatment. In other words, treatment with cellulase enzyme had no effect on the redness of DAPPJ. The a^* coordinate was high at the beginning of the processing steps due to the red-colored compounds in the apple peel. However, the redness of all samples decreased significantly ($p < 0.05$) after the enzyme incubation and UHPH treatments. The loss of redness was especially pronounced at the 0 MPa UHPH (Control) stage. This demonstrated that the compounds responsible for the red color were retained during the filtration process and did not pass into the juice. The color characteristics of apple juices are mainly affected by the presence of pigments such as polyphenols, as well as endogenous polyphenol oxidase (PPO) activity. In fruit juice processing, phenolic compounds released from the cell wall are oxidized to quinones in the presence of PPO, and color change occurs through quinones that readily convert into brown pigment (Ninga et al. 2021; Su et al. 2022). In the present study, considering that DAPP was obtained by high-temperature (250°C–300°C) drying and PPO was inactive, the contribution of non-enzymatic browning reactions to color changes can be discussed. In the case of inactive PPO, enzyme treatments can destroy the cell wall, causing phenolics to be released and oxidized by oxygen or metal ions. Furthermore, color is also affected by different non-enzymatic browning pathways such as quinone-mediated, phenol-mediated, and pectin-polyphenol interaction (Su et al. 2022; Hu et al. 2023; Xu et al. 2023).

Regarding the intensity of redness, the chroma (C^*) parameter was significantly ($p < 0.01$) affected by enzyme treatment, and lower values were obtained in the pectinase group compared to other treatment groups ($p < 0.05$). The processing stages also had an effect on the C^* parameters ($p < 0.01$), and the lowest

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TABLE 3 | Mean instrumental color parameters of DAPPJ samples treated with different enzyme types and ultra-high pressure homogenization (UHPH) treatments.

	*L**	*a**	*b**	Chroma (*C**)	Hue angle (*h*°)	Δ*E*	NBS
Enzyme treatment (ET)							
Non-enzyme	36.57 ± 1.94a	3.73 ± 4.37a	16.97 ± 6.03a	17.62 ± 6.83a	81.22 ± 9.63	2.48 ± 1.80a	2.28 ± 1.65a
Pectinase	31.12 ± 5.13b	3.51 ± 4.62b	13.90 ± 8.93b	14.55 ± 9.73b	82.21 ± 11.35	2.05 ± 1.53b	1.89 ± 1.41b
Cellulase	36.56 ± 1.92a	3.75 ± 4.38a	16.96 ± 6.02a	17.63 ± 6.85a	81.17 ± 9.64	2.48 ± 1.80a	2.28 ± 1.65a
SEM	0.028	0.021	0.023	0.019	0.441	0.013	0.012
p	**	**	**	**	NS	**	**
Processing stage (PS)							
Homogenized DAPPJ	38.23 ± 0.63a	9.25 ± 0.20a	24.80 ± 0.33a	26.47 ± 0.29a	69.55 ± 0.54c	—	—
Enzyme incubation	37.61 ± 0.52b	8.85 ± 0.19b	23.95 ± 0.24b	25.55 ± 0.26b	69.72 ± 0.37c	—	—
0 MPa UHPH (control)	30.47 ± 3.83e	0.28 ± 0.16c	9.51 ± 2.49e	9.51 ± 2.49e	88.49 ± 0.69b	0.00 ± 0.00c	0.00 ± 0.00c
100 MPa UHPH	33.65 ± 4.34d	0.06 ± 0.27d	10.88 ± 2.89c	10.88 ± 2.89c	88.89 ± 5.90b	3.48 ± 0.62b	3.20 ± 0.59b
150 MPa UHPH	33.80 ± 3.86c	−0.12 ± 0.21e	10.58 ± 2.45d	10.59 ± 2.45d	91.01 ± 1.61a	3.53 ± 0.11a	3.25 ± 0.10a
SEM	0.036	0.027	0.030	0.025	0.569	0.013	0.012
p	**	**	**	**	**	**	**
Interactions							
ET × PS	**	**	**	**	NS	**	**

Note: [a,b]: Means of the same column and in the same section having the same letters are not significantly different at $p > 0.05$ (Duncan's test) between the means of enzyme treatments. [a–e]: Means of the same column and in the same section having the same letters are not significantly different at $p > 0.05$ (Duncan's test) between the means of processing stage.
Abbreviations: ±: standard deviations; *L**: Lightness; *a**: Redness; *b**; Yellowness; Δ*E*: Total color difference; NBS: National Bureau of Standards (NBS = Δ*E* × 0.92).

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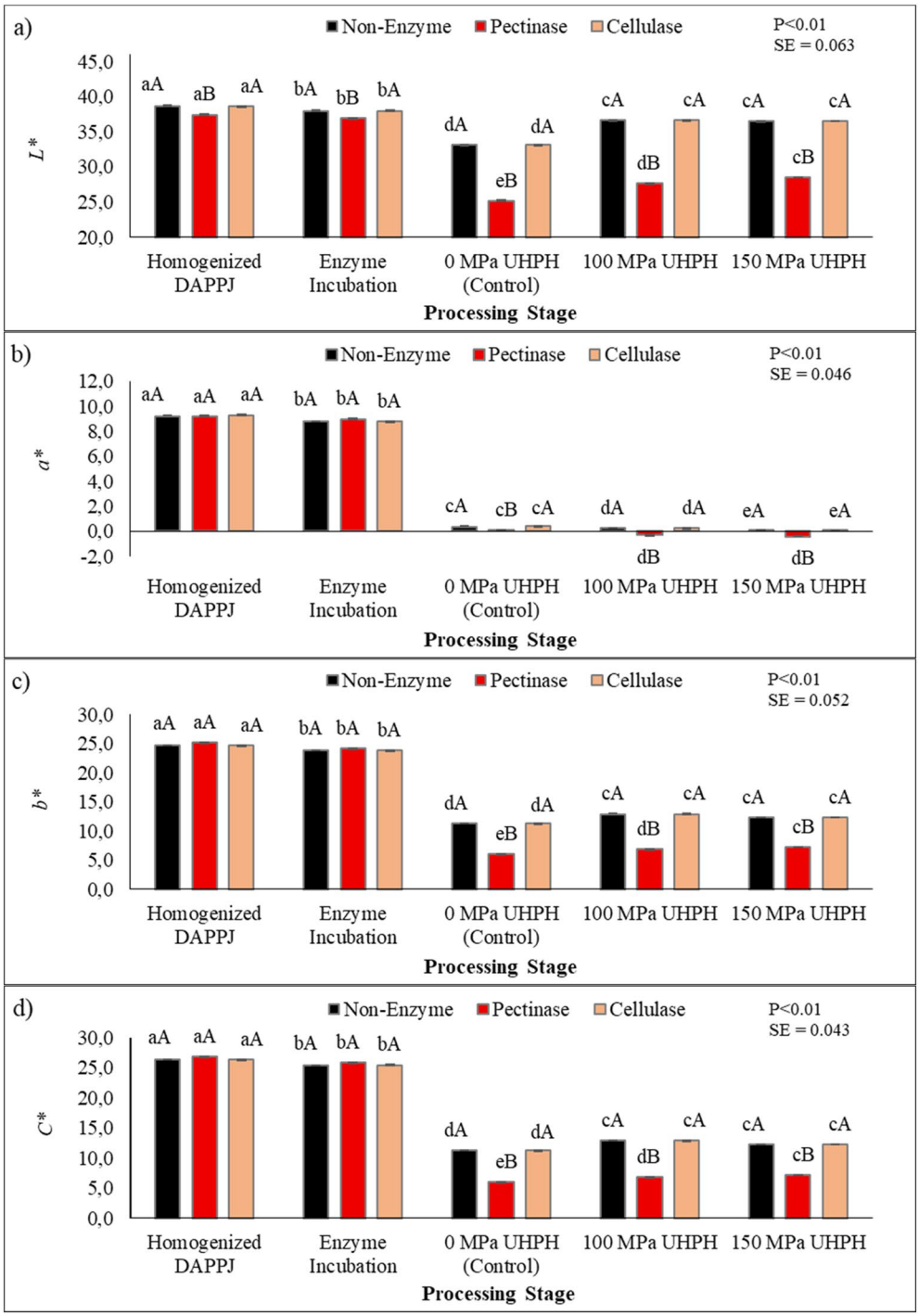

FIGURE 3 | Effect of enzyme treatment × processing stage interaction on the L^* (a), a^* (b), b^* (c) and C^* (d) parameters of dried apple pomace powder juice (DAPPJ). Lowercase and uppercase letters in bar graphs represent significant differences between processing stages per each enzyme treatment and between enzymes per each processing stage, respectively ($p < 0.05$, Duncan test).

($p < 0.05$) values were determined at the 0 MPa UHPH (Control) stage. On the other hand, 100 and 150 MPa UHPH treatment increased chroma parameters compared to the group without UHPH treatment ($p < 0.05$) (Figure 3d, Table 3). C^* parameters were similar for all treatment groups during the homogenization DAPPJ and enzyme incubation stages, but were lowest ($p < 0.05$) in the group treated with pectinase enzyme in the following stages (Figure 3d). Regarding the hue angle ($h°$) parameters, which indicate the color change from red to yellow, only the processing stages had a significant effect ($p < 0.01$), while enzyme treatment had no effect ($p > 0.05$) on this color parameter (Table 3). These values were lowest during the homogenized DAPPJ and enzyme incubation stages, and gradually increased with UHPH treatments depending on increasing pressure level ($p < 0.05$).

Various studies have indicated that the UHPH process has different effects on the L^*, a^* and b^* coordinates in different fruit and vegetable juices (Saricaoglu et al. 2019; Benjamin and Gamrasni 2020; Turan et al. 2024; Aksu et al. 2025). The effects

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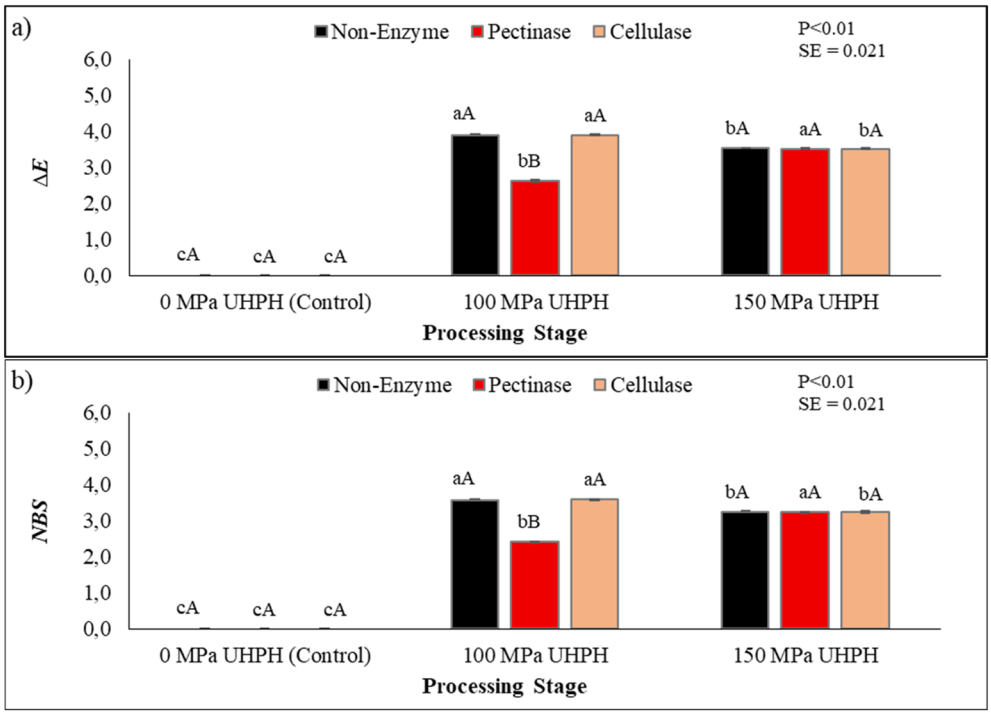

FIGURE 4 | Effect of enzyme treatment × processing stage interaction on the ΔE (a) and NBS (b) parameters of dried apple pomace powder juice (DAPPJ). ΔE: Total color difference (calculated from L^*, a^* and b values); NBS: National Bureau of Standards (NBS = $\Delta E \times 0.92$). Lowercase and uppercase letters in bar graphs represent significant differences between processing stages per each enzyme treatment and between enzymes per each processing stage, respectively ($p < 0.05$, Duncan test).

of HPH on the color of fruit juice depend largely on the food matrices and the applied processing conditions (Zhou et al. 2017). Our findings were similar to previous studies reporting that UHPH processing in a similar pressure range increased L^* and b^* coordinates while decreasing a^* coordinates in apple and orange juice (Velázquez-Estrada et al. 2019; Sauceda-Gálvez et al. 2021). On the other hand, Marszałek et al. (2023) reported that 200 and 300 MPa UHPH treatment reduced L^* and b^* coordinates and increased a^* coordinates in apple juice, but 250 MPa UHPH processing showed similar color coordinates to the control (0 MPa) group without UHPH.

For consumer acceptability in apple juice, generally low a^* and high L^* and b^* coordinates are desired. In other words, apple juices with a bright and more pronounced yellow color, along with a less pronounced greenish tone, have high consumer acceptance (Halagarda and Suwała 2018). On the other hand, Włodarska et al. (2016) reported that lightness (L^*) and clarity parameters in apple juice have a negative correlation with consumer preference. In the present study, although pectinase treatment negatively affected L^* coordinates, cellulase offered similar color parameters to the non-enzyme group. Additionally, regardless of enzyme treatments, UHPH processing increased lightness and yellowness, while reducing redness, thereby contributing to consumer acceptability.

Changes in the structure of pigments cause visible color changes during food processing, especially in fruits, vegetables, and beverages. The differences in perceptible color are evaluated by calculating coefficients such as ΔE and NBS. In this context, the effects of enzyme treatment and UHPH processes (0, 100, and 150 MPa) on the ΔE and NBS parameters of DAPPJ are shown in Table 3 and Figure 4. There was no significant ($p > 0.05$) color difference between the cellulase-treated samples and the non-enzyme group; however, the pectinase-treated samples had a lower ($p < 0.05$) mean ΔE parameters (Table 3). This can be attributed to the lower L^*, a^*, and b^* coordinates in the pectinase-treated samples compared to the other groups. On the other hand, UHPH processing resulted in a significant increase in ΔE parameter, and this increase was dependent on the UHPH level and enzyme type. As shown in Figure 4a, the effect of 100 MPa UHPH on the color difference of cellulase ($\Delta E = 3.91$) and non-enzyme ($\Delta E = 3.90$) groups was more pronounced ($\Delta E > 3$) compared to pectinase ($\Delta E = 2.63$) treatment ($1.5 < \Delta E < 3$) ($p < 0.05$). However, 150 MPa UHPH resulted in very distinct ($\Delta E > 3$) color differences with similar values ($\Delta E = 3.53$–3.54) in all groups, independent of enzyme treatment. The increase in the ΔE parameter with UHPH treatment can be attributed to particle size and distribution, as well as the induction of browning reactions resulting from the increased amount of oxygen dissolved in the fruit juice during processing (Zhou et al. 2017; Sauceda-Gálvez et al. 2021). The differences in ΔE are classified as very distinct ($\Delta E > 3$), distinct ($1.5 < \Delta E < 3$), and minor differences ($1.5 < \Delta E$) (Aksu et al. 2025). According to this classification, the effect of enzyme treatment is at the level of "distinct" and the effect of UHPH treatment is at the level of "very distinct" (Figure 4a). A similar trend was observed in the NBS parameters calculated from the ΔE parameter (Table 3, Figure 4b). Regarding the 100 MPa UHPH treatment, NBS units were similar in the non-enzyme (3.59) and cellulase (3.60) groups, but higher than those of pectinase (2.42) group. However, 150 MPa UHPH processing resulted in similar NBS units (3.24–3.25) across all enzyme groups. The differences in NBS are classified as trace (0–0.5), slight (0.5–1.5), noticeable (1.5–3.0), appreciable (3.0–6.0), much

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(6.0–12.0), and very much (≥12.0). According to NBS classification, the effect of enzyme treatment is at the level of "noticeable" and the effect of UHPH treatment is at the level of "appreciable" (Table 3, Figure 4b). In the studies conducted on the subject, it has been stated that the change in ΔE depends on the properties and structure of the raw material, temperature, UHPH level and the number of passes (Benjamin and Gamrasni 2020; Kruszewski et al. 2021; Turan et al. 2024). A similar study reported that $\Delta E > 3$ in apple juices processed with HPH, and the color difference became more pronounced with increasing pressure (from 200 to 300 MPa) (Marszałek et al. 2023).

4 | Conclusions

This study presents an innovative approach to the effective use of apple pomace, evaluating the effects of enzyme and UHPH treatments on the color, TSS, and pH properties of DAPPJ. DAPP was characterized as a valuable waste product for processing into fruit juice, featuring high phenolic content, a medium-saturation light orange-yellow color, and low pH. The non-enzyme group had lower TSS and higher pH values compared to enzyme treatments. UHPH processing after enzyme treatment was more effective in increasing TSS content compared to enzyme treatment alone. Treatment of DAPPJ with pectinase resulted in lower pH values and color (L^*, a^* and b^*) coordinates compared to the other groups. The UHPH process provided an advantage for consumer acceptance by increasing the brightness and yellowness and reducing the redness, which were negatively affected by cloth filtration. Regarding the 100 MPa UHPH treatment, color differences were more pronounced in the non-enzyme and cellulase groups. However, the 150 MPa UHPH treatment caused similar color differences in all enzyme groups. According to these results, the combination of cellulase and 150 MPa UHPH can be recommended for achieving a lighter yellow color with high consumer acceptance of DAPPJ, while the combination of pectinase and 100 MPa UHPH is more suitable for reducing visible color difference and maintaining a natural product perception. Further studies are needed to determine the bioactive, sensory, viscosity, macromolecular composition, and color stability properties of DAPPJ prepared using enzymes (single or combined) and UHPH at different pressures.

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Conflicts of Interest

The authors declare no conflicts of interest.

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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