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Development of Healthy and Clean-Label Crackers Incorporating Apple and Carrot Pomace Flours

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Abstract: The valorization of fruit and vegetable side-streams from the juice industry is an important contribution to the optimization of food resources and is an environmentally friendly practice in line with the concepts of circular economy and sustainability. The aim of this work is to incorporate them back into the food value chain by adding them as ingredients in staple foods like crackers. This is also important in terms of food fortification, as they are rich in nutrients and bioactive compounds. Crackers are popular snacks with a huge global market value, enjoyed by consumers of all ages. The current study aims to integrate flour from dried apple and carrot pomaces, resulting from juice processing, as natural ingredients with potential health benefits. The incorporation levels ranged from 20 to 40% dry weight in crackers, and their impact on physicochemical and mechanical properties was evaluated, as well as bioactivity (potential impact on health) and sensory acceptance. The addition of pomaces resulted in significant changes in texture and color, as well as enhancing the antioxidant activity of the crackers. Crackers containing pomace flours, except for the cracker with 40% carrot pomace, showed a high overall sensory acceptability and good intentions to buy.

Keywords: valorization; pomace flour incorporation; food fortification; crackers; bioactivity; sustainability

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1. Introduction

In recent years, due to knowledge of the benefits that fruit and vegetables (F&V) have on health and the demand for natural foods, F&V has become one of the first choices in a healthy diet and its consumption is strongly advised by the WHO (e.g., the "five a day program") [1–3].

Even with the fruit juice and confectionery industry having been well established for a long time, F&V are still accountable for up to 20% of food waste and losses along the food supply chain [4]. Therefore, the side-streams from these industries can be stabilized by drying and grinding waste into flours rich in fiber and bioactive compounds, to be used like natural food ingredients and to enhance the health benefits and technological functionality of several food products.

Major food trends show that the production of F&V has steadily increased worldwide. For example, the total production rose up to 59 and 68% between 2000 and 2021, reaching 910 and 1150 million tons, respectively [5]. Almost 50% is processed as juice, and millions of tons of waste are being generated that could be a big challenge for the environment, but at the same time this could be considered an interesting side-stream, as this waste is known to be a source of functional compounds such as phenolics and fiber [6–8]. An advantage of that combination (fiber and phenolic compounds) is their bound capacity, as fiber can deliver bioactive compounds and act as a vehicle for their transport along the gastrointestinal tract, allowing their release in the gut after fiber fermentation by the gut microbiota. To this purpose, the valorization of pomaces as food ingredients could be an interesting and efficient way to promote health benefits [9,10].

Fiber refers to a group of carbohydrate polymers with ten or more monomers and a degree of polymerization (DP) higher than 10 that are not readily digestible nor absorbable in the small intestine, but could be fermentable by the human gut microbiota [11,12]. Examples include indigestible oligosaccharides, cellulose, hemicellulose, arabinoxylan, β-glucan, inulin, gum, pectin, and resistant starch [12,13]. Several studies show the link between taking in adequate fiber and a healthy gut and reduced risk of depression, obesity, and chronic diseases such as diabetes type 2 and cardiovascular and coronary heart disease [13–15].

Phenolic compounds are molecules characterized by an aromatic ring and one or more hydroxyl substitutes, and their binding capacity to mono- and polysaccharides increases their structural heterogeneity. For that reason, more than 8000 phenolics can be identified in nature and almost 75% of them are flavonoids in plants [16]. Fruits in particular are considered rich sources of flavonoids and phenolic acids, including gallic, ellagic, and vanillic acids. These compounds are important for their therapeutic potential as they can act as free radical scavengers or antioxidants, participating in the oxidative stress process, which may play a decisive role in the aging process and the development of many neurodegenerative, metabolic, and inflammatory disorders [17,18].

Concurrent with the rising demand for foods with functional and healthier properties, snacking has become a huge trend, with a value estimated at EUR 495.60 billion in 2023 and is expected to grow with a CAGR of 6.29% during the forecast period of 2023–2028 [19]. Consumers all over the world are moving towards preferring food that is easy to carry and readily accessible, making snack foods one of the best options [20]. Food industries are now launching fortified products enriched with vitamins, protein, and nutrients, giving consumers snacks with nutritional support [21].

Food functionality can be enhanced by using F&V pomace due to its functional qualities. Many types of pomace are used in a broad range of baked goods, including cakes, muffins, cookies, rock buns, and crackers [22–27]. To the best of our knowledge, there is a lack of information in the literature on the maximum level of incorporation of pomaces to develop crackers with the highest phenolic content and antioxidant activity. The present work studied the influence of replacing wheat flour with carrot and apple pomace flours (CPF and APF, respectively) in different percentages up to 40% in crackers to be consumed in snacking. The influence on the physicochemical and sensory properties and on the antioxidant capacity of wheat-based crackers was evaluated, as well as the sensory acceptability.

2. Materials and Methods

2.1. Materials

2.1.1. Chemicals

Methanol and ethanol were purchased from Fisher Chemicals (Fair Lawn, NJ, USA). DPPH (2,2-diphenyl-1-picryl-hydrazyl-hydrate), Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid), acetic acid, sodium acetate, TPTZ (2,4,6-tris(2-pyridyl)-s-triazine), hydrochloric acid, iron (III) chloride hexahydrate, Folin–Ciocalteu reagent, sodium carbonate, gallic acid, calcium chloride, and sodium hydroxide were obtained from Sigma-Aldrich (Saint Louis, MO, USA). Ultrapure water was purchased from the Synergy® Water Purification System from Merck Millipore (Burlington, MA, USA). All chemicals used were of analytical or HPLC grade.

2.1.2. Ingredients

AP and CP flours were provided by ALITEC—Alimentos Tecnológicos SA (Nazaré, Portugal). Due to the high moisture level in pomaces and the high risk of microbial contamination and oxidation, the drying procedure was conducted by the company using a drying tunnel (Tecnofruta, Valencia, Spain) at 80–85 °C and 55 Hz of air flow for 110 min, and pomaces were ground and packaged afterwards (Ferneto, Vagos, Portugal). Other ingredients for cracker preparation, including wheat flour T55 (76% carbohydrates, 10% protein, 3.5% fiber, and 1.3% fat), baking powder, fine sea salt, white sugar, and vegetable oil, were purchased from the local market.

2.2. Methods

2.2.1. Proximate Composition

Pomace flours were analyzed in terms of moisture, minerals, ash content, total fat, crude fiber, and crude protein following the international standard methods. Moisture and ash content were determined gravimetrically (AACC method 44-15.02) [28]. Minerals (Na, K, Ca, Mg, P, S, Fe, Cu, Zn, Mn, and B) were estimated using Inductively Coupled Plasma—Optical Emission Spectroscopy (iCap Series-7000 plus series ICP-OES, Thermo Fisher Scientific, Waltham, MA, USA), following the procedure described by Marrero et al., (2013) [29], and according to AACC 40-75.01 [30]. Total fat was determined by the Soxhlet method according to AACC 30-25-01 [31]. Crude fiber was determined by the Weende method (AOAC method 978.10) [32]. Crude protein was determined by using an NDA 701 Dumas nitrogen analyzer and the common conversion factor of 6.25 [33]. Total starch quantification was performed by using the Megazyme Total Starch (AA/AMG) Assay kit and following the Rapid Total Starch (RTS) method, that is, according to AOAC method 996.11 with a slight modification [34].

2.2.2. Crackers Manufacture

Crackers were prepared according to the following formulation, developed in our lab in previous studies [35], with 59% commercial all-purpose wheat flour T55, 1.5% baking powder, 1% salt, 1% sugar, 7.5% vegetable oil, and 30% distilled water (w/w). Pomace flours, at 20 and 40% (w/w) incorporation levels (AP20 and CP20, AP40 and CP40, for 20% and 40% of incorporation of apple and carrot pomaces) were added to the same formulation by substituting a corresponding amount of wheat flour. In the case of the 40% crackers, the water content was increased and adjusted to develop a workable dough with suitable consistency. The ingredients were weighed based on a 300 g batch and mixed in a food processor (Bimby, Vorwerk, Germany) to obtain a homogeneous dough. Then, the dough was left to rest for 10 min and then laminated into thin sheets using a pasta roller machine. The laminated dough was divided into pieces using a square mold (75 × 75 mm). Each piece was then slightly perforated. Next, the crackers were baked at 180 °C in a forced-air convention oven (Unox, Cadoneghe, Italy) for approximately 10 min. Then, they were dried for 30 min at 60 °C and cooled for 30 min at room temperature, and then placed in hermetic glass jars for storage. Part of the cracker batches were promptly ground into powder using the food processor (Bimby, Vorwerk, Germany), and then frozen for further biochemical analysis and antioxidant potential evaluation.

2.2.3. Dough Rheology

Viscoelastic Behavior

The small amplitude oscillatory shear (SAOS) rheology measurements were conducted using a rheometer (Haake Mars III—Thermo Scientific, Dreieich, Germany) with a UTC—Peltier system to determine the viscoelastic properties of the dough, with and without APF and CPF, at 20 °C. The stress sweep test at 1 Hz was performed for the determination of the linear viscoelastic region to select the critical stress to be applied during the SAOS measurements. Then, the frequency sweep test allowed the acquisition of the storage (G') and loss (G'') moduli at frequencies ranging from 0.01 Hz to 100 Hz, while maintaining a constant shear stress within the linear viscoelastic region of each sample. Each sample (control; AP20; AP40; CP20 and CP40) was placed in the bottom plate of a 20 mm serrated parallel plate (PP20) with a 1 mm gap. To stop moisture loss during testing, liquid paraffin was applied to the sample edges. Each formulation was tested at least in triplicate.

Mixolab—Mixing and Pasting Curves

The impact of APF and CPF incorporation at 0%, 10%, and 20% w/w wheat flour basis on the dough during mixing and pasting was assessed using the Mixolab2 instrument (Chopin Technologies, Paris, France), following the Chopin+ protocol, at a constant water absorption of 55 g/100 g, determined in a previous test. The test settings used were similar to those described by [36]. In the case of the 40% pomace incorporation, the dough was too tough to be tested; it was over the limits of the torque in this equipment.

The Mixolab parameters evaluated were as follows: water absorption (WA% at 14% moisture basis): the amount of water required to achieve a dough of appropriate consistency (target); dough development time (DDT): the time it takes for dough to develop during mixing to reach C1 (maximum torque during mixing to determine water absorption); dough stability (DS): the duration during which the dough maintains its structural integrity around C1—11% [37]; C2 (Nm): minimum torque value when the Mixolab starts heating the dough, reflecting the gluten quality; C3 (Nm): peak torque obtained after C2, expressing starch gelatinization; C4 (Nm): decrease after C3, representing the cooking stability; and C5 (Nm): the torque value obtained by the end of the test, representing starch gelification during the cooling stage [36]. The results are in triplicate for each blend, as well as for the control.

Dimensions

The characteristic dimensions, width (W) and thickness (T), of 10 crackers from each formulation were measured using a digital caliper model 684132 (Lee Tools, Housten, TX, USA). The spread ratio (W/T) was calculated accordingly.

2.2.4. Color

With a CIE standard illuminant D65, a 2-degree field of view, and a d/0° viewing angle, the Minolta CR-400 (Japan) colorimeter was used to measure the color of the cracker samples. The results were expressed in terms of L^*, lightness (values increasing from 0 to 100); a^*, redness to greenness (60 to −60 positive to negative values, respectively); and b^*, yellowness to blueness (60 to −60 positive to negative values, respectively) according to the CIELab system. By applying the formula $\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$, the total color difference between the crackers was calculated using average $L^*a^*b^*$ values. The measurements were performed with a white standard (L^* = 94.61, a^* = −0.53, and b^* = 3.62) at room temperature and under the same light conditions. Measurements were replicated ten times for each formulation (one measurement per cracker).

2.2.5. Moisture Content and Water Activity

These properties were measured with a PMB Humidity Analyzer (AE Adam GmbH, Felde, Germany), after checking it against the reference gravimetric method and LabMaster–aw neo (Novasina AG, Lachen, Switzerland).

2.2.6. Texture

Instrumental texture analysis was carried out in a TA.XTplus (Stable Micro Systems, Godalming, UK) texturometer. "Three-point bending" or "snap" tests were performed using a double clamp set and 3 mm thick knife blade at 1 mm/s probe speed, with a 5 kg load cell, and at a controlled (20 ± 1 °C) room temperature. Three textural parameters of the cracker were evaluated: peak force or hardness (N), first break distance or brittle deformation (mm), and total area of work or total energy at rupture or toughness (J).

2.2.7. Sensory Analysis

Cracker samples with 20 and 40% of pomace flours, as well as the control samples, were tested by an untrained sensory analysis panel (n = 44, age: 18–49). The cracker samples were evaluated in terms of appearance, color, smell, taste, texture, and overall acceptability (six levels, to avoid the center bias, from "very pleasant" to "very unpleasant").

The buying intention was also assessed, from "would certainly buy" to "certainly wouldn't buy" (four levels). In compliance with EN ISO 8589 standard, the assays were carried out in a standardized sensory analysis room [38].

2.2.8. Antioxidant Potential

To prepare sample extracts, 2 g of pomace flours or cracker powders were weighed in a test tube and extracted with 20 mL of ethanol 96% at ambient temperature mixed using an overhead shaker (Heidolph Instruments, Schwabach, Germany) overnight. Then, the extracts were centrifuged at 3220 g for 10 min. The supernatant was recovered and stored at −24 °C until use.

To evaluate the radical scavenger potential, the DPPH assay was performed by mixing 3.9 mL of DPPH radical solution (0.06 mM in methanol, Sigma-Aldrich, St. Louis, MO, USA) and 100 µL of sample extract. The reaction mixtures were vortexed and incubated in darkness at room temperature for 40 min and the absorbance was measured at 515 nm. The antioxidant capacity of the samples was expressed in terms of µmol of Trolox equivalent antioxidant capacity (TEAC) per g of sample (Trolox calibration curve: 0 to 1000 $\mu g.mL^{-1}$, R^2 = 0.9958) and corresponding radical scavenging activity (RSA). A control assay without pomace extract was also performed. Analyses were conducted in triplicate.

Another way of looking at the antioxidant potential is by measuring the ferric reducing power through FRAP assay. This was performed by mixing 2.7 mL of FRAP solution, 270 µL of distilled water, and 90 µL of sample extract. The reaction mixtures were vortexed and incubated in a water bath at 37 °C for 30 min and the absorbance was measured at 595 nm. The antioxidant capacity of the samples was expressed in terms of µmol of TEAC per g of sample (Trolox calibration curve: 0 to 800 $\mu g.mL^{-1}$, R^2 = 0.9971). Analyses were conducted in triplicate.

2.2.9. Total Phenolic Content

The TPC was determined using the Folin–Ciocalteu method and gallic acid as a standard, as proposed earlier by Singleton and Rossi, 1965. To 150 µL aliquots of each sample, 2.4 mL of deionized water and 140 µL of Folin–Ciocalteu reagent (Sigma-Aldrich, St. Louis, MO, USA) were added and vortexed. After 3 min, 300 µL of sodium carbonate was added and vortexed again and then stored in darkness at room temperature for 2 h. The absorbance of each sample was measured at 725 nm. Results were expressed in gallic acid equivalents (mg GAE g^{-1}) through a calibration curve (gallic acid: 0 to 200 $\mu g.mL^{-1}$, R^2 = 0.9998) (Sigma-Aldrich, St. Louis, MO, USA).

2.2.10. Statistical Analysis

Statistical analysis of the experimental data was performed using SPSS (version 29, IBM, Armonk, NY, USA), through variance analysis (one-way ANOVA), and by the Tukey test as the post hoc at a significance level of 95% ($p < 0.05$). All results are presented as average ± standard deviation.

3. Results and Discussion

3.1. Physicochemical Characteristics of the Raw Pomaces and Crackers

The results for the proximate composition of APF, CPF, and crackers are shown in Table 1. It is worth noticing that the moisture content is about 60% higher in CP than in AP, and a value below 14.5% is considered the limit value for stable flours in cereals [39]. As side streams, pomaces are not taken into full consideration and, therefore, after the juice extraction, they are submitted to a dying process at 80/85 °C for 110 min. But since the final moisture content depends on several factors, namely the drying process and conditions, to be able to re-introduce these by-products into the food chain again, appropriate industrial controlled routines must be implemented. In the case of crackers, the lower moisture content of crackers including APF compared to ones including CPF could be due to the difference in the initial moisture content of the pomaces and the cooking time.

Table 1. Proximate composition of the apple and carrot pomace flours and crackers (% dw). Results are expressed as average ± standard deviation (n = 3), followed by an alphabet letter. Different letters mean different significant results (Tukey's HSD; $p \leq 0.05$).

Sample	Moisture	Ash	Fiber	Fat	Nitrogen	Carbohydrates, Including Starch	Starch
APF	10.8 ± 1.08 ^{a}	1.3 ± 0.01 ^{a}	21.9 ± 0.84 ^{a}	1.8 ± 0.13 ^{a}	0.7 ± 0.01 ^{a}	59.7 ± 2.39 ^{a}	13.8 ± 0.49 ^{a}
CPF	18.9 ± 0.31 ^{c}	7.3 ± 0.07 ^{b}	10.9 ± 0.37 ^{b}	1.0 ± 0.12 ^{b}	1.3 ± 0.01 ^{b}	51.3 ± 4.40 ^{b}	5.8 ± 0.23 ^{b}
WF	14.1 ± 0.45 ^{b}	0.5 ± 0.02 ^{c}	0.5 ± 0.01 ^{c}	1.0 ± 0.04 ^{b}	1.3 ± 0.01 ^{b}	76.1 ± 0.44 ^{c}	75.3 ± 0.51 ^{c}
Control	4.2 ± 0.28 ^{d}	2.4 ± 0.08 ^{d}	1.1 ± 0.06 ^{d}	10.4 ± 0.02 ^{c}	1.5 ± 0.02 ^{c}	72.7 ± 0.31 ^{d}	51.1 ± 0.85 ^{d}
AP20	2.3 ± 0.10 ^{e}	2.8 ± 0.15 ^{e}	1.4 ± 0.30 ^{d}	11.0 ± 0.05 ^{d}	1.3 ± 0.00 ^{b}	74.3 ± 0.37 ^{d}	49.5 ± 0.56 ^{de}
AP40	2.5 ± 0.09 ^{e}	2.9 ± 0.05 ^{e}	5.4 ± 0.55 ^{e}	11.3 ± 0.39 ^{d}	1.1 ± 0.01 ^{d}	70.4 ± 1.38 ^{d}	48.8 ± 0.11 ^{e}
CP20	3.2 ± 0.18 ^{de}	3.4 ± 0.03 ^{ef}	1.3 ± 0.04 ^{d}	10.1 ± 0.15 ^{c}	1.4 ± 0.01 ^{e}	73.1 ± 0.10 ^{d}	44.8 ± 0.14 ^{f}
CP40	3.5 ± 0.13 ^{de}	4.1 ± 0.07 ^{f}	2.6 ± 0.17 ^{f}	10.8 ± 0.05 ^{d}	1.3 ± 0.00 ^{b}	70.9 ± 0.14 ^{d}	39.2 ± 0.46 ^{g}

Superscript, lowercase letters indicate the significant differences between different fractions. APF: apple pomace flour; CPF: carrot pomace flour; WF: wheat flour; Control: cracker without pomace; AP20: cracker with 20% apple pomace flour; AP40: cracker with 40% apple pomace flour; CP20: cracker with 20% carrot pomace flour; CP40: cracker with 40% carrot pomace flour.

Regarding ash content, as expected, the value in carrot pomace is 5.6 times higher than in apple pomace, and this is consistent with the detailed results from the individual minerals content (Table S1). In fact, as carrot is a root and apple is a fruit, the proximity to the soil and the function of the root, absorbing water and minerals to feed the plant, might explain this difference [40,41]. Subsequently, crackers incorporating 20 to 40% of CPF have the highest ash content (3.4 and 4.1% dw) compared to the AP20 and AP40 (2.8 and 2.9% dw), respectively.

Results for fiber are much higher for apple (almost 2-fold), probably because the pomace is enriched in apple skin, seeds, and stalks [42]. Accordingly, AP40 has double the content of fiber compared to CP40, as expected. The fat content of both apple and carrot pomaces is considerably low (between 1 and 1.8% dw), and is slightly higher in apple pomace, as the apple skin has some non-polar components at the surface, contributing to the overall fat composition [43].

For protein results, when using the value from the Dumas equipment, without the conversion factor, for nitrogen, the value for carrot, again as a root and involved in taking the nitrogen out from the soil, is two times higher than in apple pomace. This does not mean that carrot has more protein, and this was the reason we decided to keep the values without applying the conversion factor of nitrogen into protein. Since wheat flour has more protein (10% dw) and nitrogen (see Section 2.1.2), the incorporation of pomaces results in the reduction in the nitrogen content of crackers, particularly in the case of AP40, in which the nitrogen content is the lowest (1.1% dw).

Carbohydrates were calculated as the difference for the other compounds after converting nitrogen into protein by a factor of 6.25, and the value was markedly higher in apple pomace. However, for crackers, there is no significant difference in carbohydrates when incorporating APF and CPF, which could be due to the degradation of carbohydrates during the Maillard reaction or caramelization, which could possibly happen when cooking at 180 °C [44–46]. Regarding the starch, CPF has a lower content than APF, which is mainly due to the fact that carrot, as a root, has only negligible amounts of starch and these gradually diminish before harvest. And these results are consistent with the results obtained for crackers. It has also been shown that the increase in pomace substitution with wheat flour leads to a remarkable reduction in starch in the final product. The presence of seeds possibly contributes to the higher content of starch in APF [47].

Analyzing the mineral composition presented in Table S1, both pomaces are enriched in potassium, and this is particularly higher in carrot pomace (almost 5-fold when compared to apple pomace). As a root, carrot accumulates a high concentration of minerals that are diffused from the soil towards the roots. Phosphorus, calcium, and sodium were also identified in considerable amounts.

3.2. Rheology of Cracker Dough

The rheological properties of different formulations were analyzed using the small amplitude oscillatory shear (SAOS). The presence of specific structures that can partially store energy and partially recover upon stress release gives rise to the material's viscoelastic properties. When the applied stress is released, a significant portion of the same energy will be lost irretrievably. Thus, certain materials are known to exhibit both elastic and viscous behaviors. An oscillating rheometer can be used to record variations in the conservative and loss moduli's values based on temperature and frequency [48]. The analysis involves two parameters: G′ and G″. The storage modulus (G′) represents the portion of energy that can be utilized to recover deformation and describes the proportion of elastic properties in the material under study. Conversely, the portion of energy lost or dispersed during sinusoidal deformation is characterized by the loss modulus (G″) [49]. The mechanical behavior at 20 °C is presented in Figure 1 by a frequency sweep from 0.01 up to 100 Hz using a stress value within the viscoelastic region (structure is not damaged), previously determined by a stress sweep at 1 Hz.

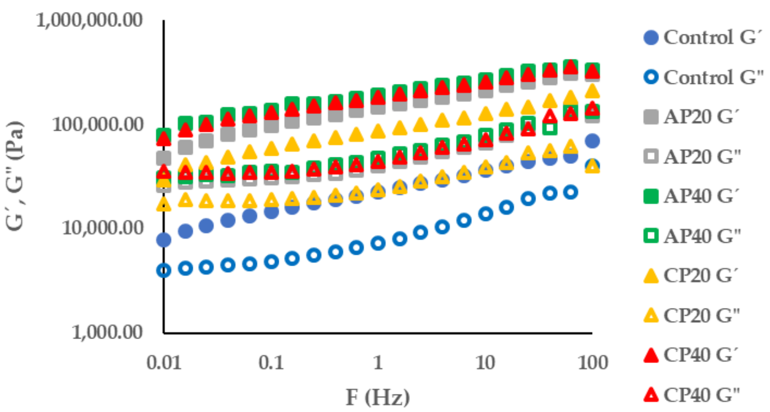


Figure 1. Mechanical spectra (G′ and G″ as a function of frequency) of cracker doughs at different levels of incorporation of apple and carrot pomace flours.

Figure 1 shows the frequency sweep (or mechanical spectrum) of cracker doughs with the addition of apple and carrot pomaces. The values of the G´ and G″ moduli depend on the internal structure of the systems.

It was found that, in each analyzed case (Figure 1), the elastic properties predominated over the viscous ones, with the conservative modulus (G´) values being higher than the loss modulus (G″). The presence of pomaces in the formulation and their growing share increases the values of G′ and G″ moduli and spectra, which are all higher by about tenfold in Pa values, compared with the control. The behavior of cracker doughs is viscoelastic, with G′ being higher than G″ and both values being frequency-dependent, as is the general characteristic behavior of doughs. There is a difference between the addition of 20% apple and 20% carrot pomace flours, with a higher impact for apple pomace flour addition, which can be seen on values for G′ at 1 and 10 Hz (Figure 2); this could be due to the higher level of starch (more than 2-fold) in apple pomace. However, there are no substantial differences between the spectra of 40% apple pomace addition and 40% of carrot, as they all have a considerable amount of carbohydrates, over 50%, increasing the dough consistency but not modifying the spectra trend and balance between elastic and viscous components. In fact, based on G′ values extracted from the frequency sweep at 1 Hz and 10 Hz (Figure 3), one can confirm that the addition of pomace exerted an evident effect, increasing the value of the dynamic viscoelastic properties of the dough.

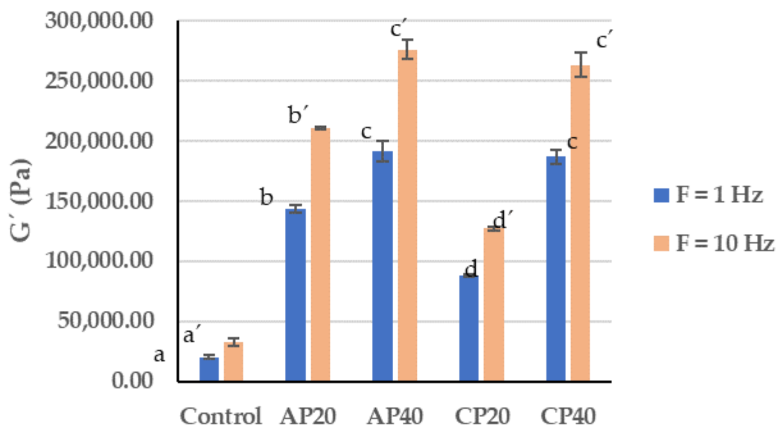


Figure 2. Storage modulus of cracker doughs with apple and carrot pomace at frequencies of 1 and 10 Hz. Results are expressed as average ± standard deviation of triplicates (n = 3), followed by an alphabet letter. Different letters mean significant different results (Tukey's HSD; $p \leq 0.05$).

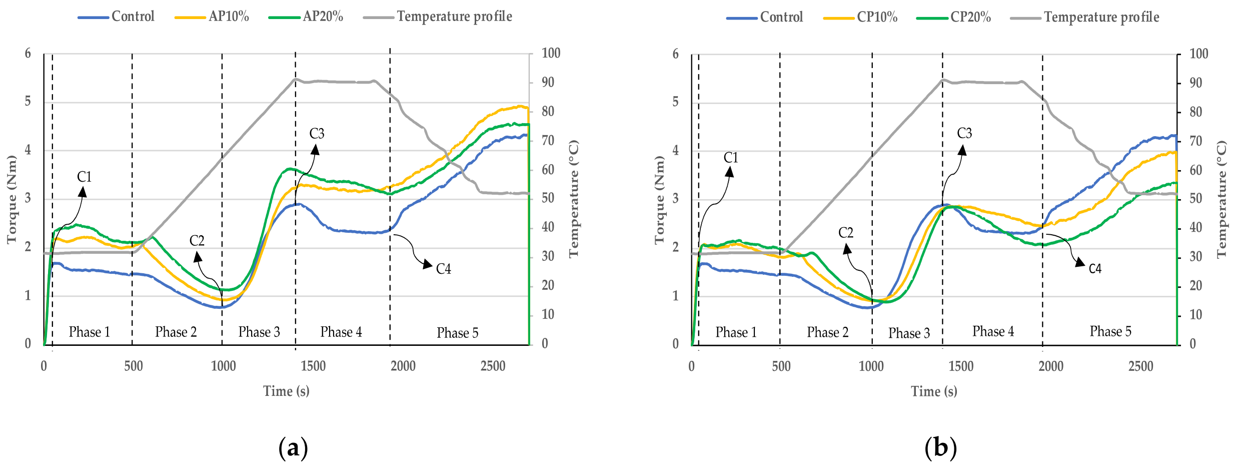


Figure 3. Mixolab curves of (**a**) mixture of wheat flour with 10 and 20% apple pomace flour and (**b**) mixture of wheat flour with 10 and 20% of carrot pomace flour vs. wheat flour.

3.3. Evaluation of the Mixing and Pasting Characteristics

The Mixolab Chopin+ protocol [50] was performed to evaluate the influence of incorporating apple and carrot pomace flours at different levels on the mixing and pasting behavior of the mixture of wheat flour and pomace flour at a constant water absorption level (55 g/100 g) (Figure 3). This method determines the consistency of dough as the torque exerted by the dough on the kneading pieces, reproducing the overall processing during kneading and the first part of baking to follow the behavior of the protein matrix at a constant temperature (30 °C), followed by the role of starch by applying temperature profile heating at about 90 °C, and subsequently cooling down to 50 °C. The decision to use constant water absorption was taken to allow us to compare the behavior of the different dough systems.

In the first phase of the analysis, dough development time (DDT), the time needed for the gluten network to form (the time needed to reach the first peak in torque—C1), is an essential parameter to evaluate. For wheat flour, this period usually ranges from 0.99 to 7.36 min, and strong flours are characterized by showing a long DDT. The C1 is influenced mainly by the quality of the protein, which is responsible for the gluten matrix, the size of starch granules, and the level of starch degradation [51,52]. C1 and DDT show an increasing trend for doughs with both pomace flours; in accordance with the increase in viscoelastic parameters, the fiber and starch present in pomaces dilutes the gluten and increases the time taken to develop the inner structure of the dough.

The value of stability for different wheat-based flours ranges between 1.43 and 9.13 min [53,54]. The Mixolab method to calculate stability is complex (the time during which the upper frame is bigger than C1–11%). Therefore, stability was determined using the time the dough stayed at a stable value of consistency (Nm). For the additions of apple pomace flour (Figure 3a), the stability of the dough was reduced due to a dilution effect of the wheat gluten. However, the stability was not affected much by the carrot pomace flour additions (Figure 3b), and the high levels of hemicelluloses in roots should be responsible for this. Nevertheless, the torque was always higher with the addition of pomace flours, demanding compensation with a specific amount of added fiber due to the reduction in gluten and starch contents.

In the second stage, when warming starts, the torque decreases to the minimum value (C2) which was attributed to the weakening of the internal network under mechanical shear stress and protein destabilization [51,55,56]. The decrease in torque from C1 to C2, as well as its rate (given by the slope α), was higher after the addition of pomace flours compared to the control, although C2 values were all very similar. This must be due to the dilution of the gluten content and the protein's weaker network.

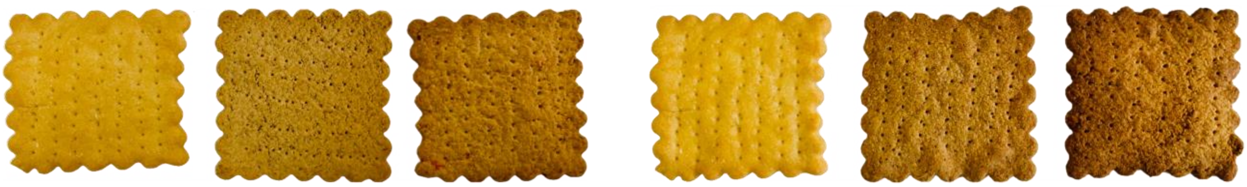
The third phase of the mixolab, when it reaches its top temperature (about 90 °C), was evaluated via the C3 and slope β parameters. The C3 torque ranged from 2.9 (control) up to 3.6 Nm (AP20) due to the presence of an increased amount of fiber, in accordance with the results from the rheometer. This can be explained by the higher content in starch of the apple pomace, compared to the carrot, and a good synergy remaining with the wheat starch. A similar trend is also noticeable for the slope β, an indicator of starch gelatinization rate, running in parallel, but C3 peaks increase with apple pomace addition and keep the same value as carrot pomaces.

This temperature-regulated testing after phase 1 gives emphasis to the phenomena which occurred mainly with starch and fiber, represented by the C4 decreasing torque. This phase relates to the vulnerability of the gelatinized starch granule to the enzymatic hydrolysis by amylases [51]. The highest hot gel stability, i.e., the value of minimum torque, was observed for the samples containing apple pomace (C4 = 3.2), probably due to the highest content of starch.

The starch gellification phase 5 was different for the apple and the carrot pomaces. For the former, the gel strength was higher than the control, as apples have a lot of starch, especially if they are not too ripe. For carrots, the fibers were not so prone to become organized and form a gel matrix with the wheat starch at the end, and the torque was lower than the control.

3.4. Color and Dimensions

The pomace crackers exhibited different, visually appealing colors, as shown in Figure 4. The color parameters in terms of lightness (*L**), balance between redness and greenness (*a**), and balance between yellowness and blueness (*b**) are represented in Figure 5.



(**a**) (**b**)

Figure 4. Cracker control vs (**a**) AP20 and CP20 and (**b**) AP40 and CP40 (from left to right).

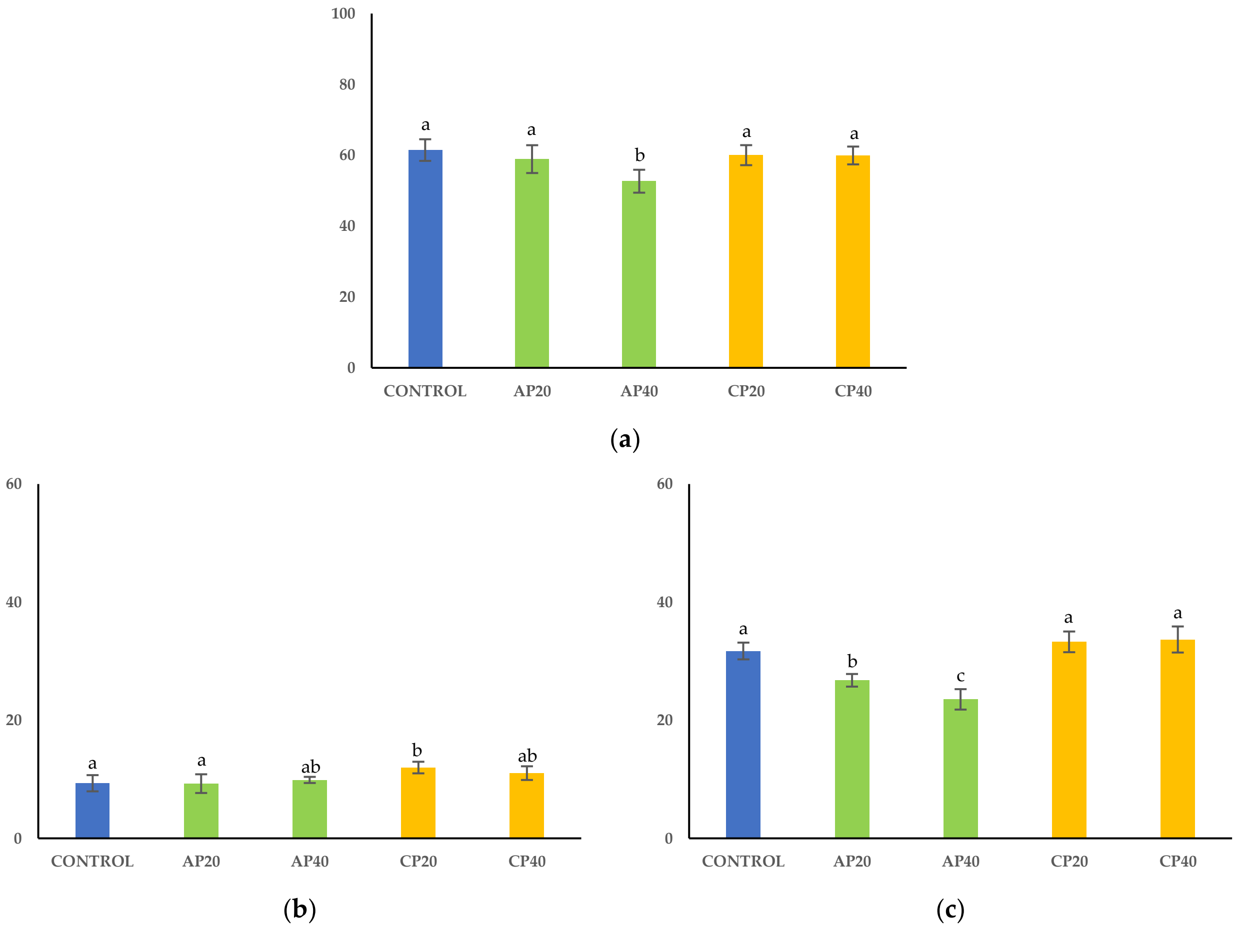


Figure 5. The color parameters of crackers: (**a**) lightness (*L**), (**b**) balance between redness and greenness (*a**), (**c**) balance between yellowness and blueness (*b**). Results are expressed as average $\pm$ standard deviation (n = 10), followed by an alphabet letter. Different letters mean significantly different results (Tukey's HSD; $p \leq 0.05$).

The incorporation of pomace flour did not result in any significant changes in relation to the control (*L** 61.5) in terms of lightness, except for crackers with 40% AP that showed a darker color. For crackers with AP, the lightness decreased significantly from 58.9 to 52.7 when increasing the incorporation level from 20 to 40%, but no significant changes were observed between crackers with 20 and 40% CP. The reason could be related to the higher amount of simple reducing sugar contained in apple compared to carrot and wheat flour which, during cooking, undergoes a Maillard reaction, conferring a darker color on the final product.

Regarding *a**, crackers showed positive values in the red domain and there was no difference between the control and with AP, but when CP was incorporated, there was an evident increase. However, concerning *b**, an opposite trend was observed in which CP did not show any significant difference to the control, contrary to AP. The result revealed a decrease in yellowness and redness in crackers with AP and CP, respectively, by increasing the amount of pomace included. The reaction kinetics of pigment degradation, namely β-carotene in carrot and Lutein in apple, upon a high temperature during baking, might be dependent on the initial pigment concentration [35]. Furthermore, the Maillard reaction between proteins and reducing sugars in both sources resulted in the formation of brown-colored compounds like melanoidins, which affect visual color perception and consequently the placement of the sample within the *L*a*b** in the tridimensional space. In addition, the volume changes and moisture loss that take place during baking can also have a significant impact on the crackers' appearance. As will be discussed later, crackers which presented lower dimensions and lower water content showed that those parameters can influence the color perception and accelerate surface browning [57].

The results of the total color differences between wheat-flour-based crackers (WF) used as the control and those that included pomace flours from both apple and carrot are shown in Table 2. A noticeable impact on color was seen when 20% and 40% of the apple and carrot pomace flours were added ($\Delta E^* > 5$) [53].

Table 2. Total color difference calculated for the crackers with apple and carrot pomace flour at different levels of incorporation in comparison with the WF cracker (control). Data expressed as means.

Sample	ΔE*
Control	-
AP20	10.58
AP40	10.97
CP20	11.10
CP40	11.15

Characteristic dimensions of all crackers are presented in Figure 6. It was observed that there was a significant ($p < 0.05$) reduction in the crackers' thickness (1.8–2.2 mm for AP and 2.0–2.8 mm for CP) when compared to the control (3.3 mm) when increasing the amount of pomace flour. This decreasing trend is related to the incapacity of the dough to expand during baking, as wheat gluten, responsible for this volume increase by building the network that holds the gas produced during leavening, is diluted. In addition, the presence of fiber that interferes with starch gelatinization, competing for water, will further reduce the expansion of the structure, which is a crucial factor for product development. These differences led to higher spread ratios for the pomace crackers, which were statistically significant ($p < 0.05$) for all incorporation levels.

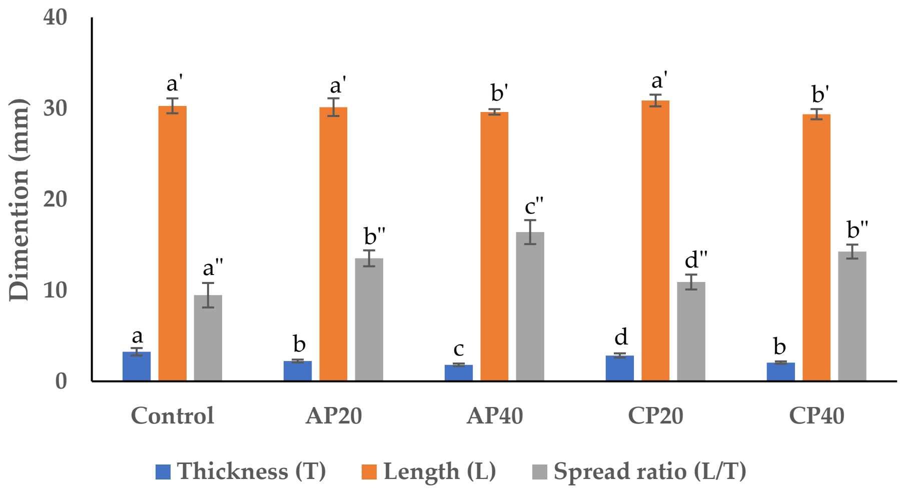


Figure 6. The texture parameters of crackers. Results are expressed as average ± standard deviation (n = 10), followed by an alphabet letter. Different letters mean significantly different results (Tukey's HSD; $p \leq 0.05$).

3.5. Moisture Content and Water Activity of Crackers

The quality parameters in low-moisture foods are influenced by water content and/or water activity (aw), which has a significant impact on their crispiness and sensory appeal. The food materials became softer and more stale and lost their crispiness above a critical aw value, typically around 0.5 [58,59].

According to Figure 7, the control cracker presented an initial aw of 0.3 and with the addition of pomaces, the aw decreased significantly with apple but not for carrot, due to its higher level of moisture content (18%). The decrease in aw corresponds to highly crispy products [58], but for the cracker with 40% of carrot pomace the aw increased up to 0.4, determining a softer texture which was not well appreciated by the panel in the sensory analysis (to be discussed later in Section 3.7).

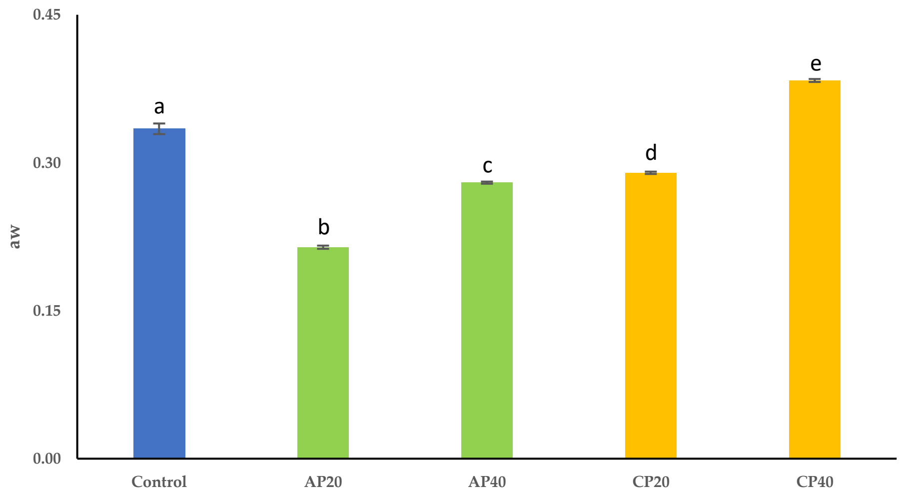


Figure 7. Evaluation of the water activity (aw) of crackers. Results are expressed as average ± standard deviation (n = 10), followed by an alphabet letter. Different letters mean significantly different results (Tukey's HSD; $p \leq 0.05$).

Regarding the water content (Table 1), the same behavior was observed but without overpassing the control level (4.2). Also, in this case, the apple crackers still showed a better crispiness (2.32–2.45), which is the main parameter of texture acceptance for this category of product. It is possible that adding pomace in large quantities will result in a weaker gluten network that is less effective at trapping gas bubbles and water molecules. This result means that the addition of pomaces, particularly for apple pomaces, has a positive impact on the texture of the crackers.

3.6. Texture

Since consumers value a crunchy and crisp texture highly, texture is one of the key factors in cracker appreciation [60]. One of the most suitable instrumental analysis tests to assess the texture of these kinds of brittle food samples is the "three-point bending" or "snap" test, in which the cracker is leaned upon two support beams while a third moves down (parallel) into the middle point of the sample, causing the sample to fracture into two equal pieces.

The crackers with 20% incorporation showed significant ($p > 0.05$) decreases in hardness and toughness in relation to the control crackers, although there seemed to be a tendency for both parameters to increase with the 40% addition of pomace. However, a different behavior was detected with the deformation results. With AP, there was a positive correlation between the amount incorporated and the deformation, and therefore the brittleness reduced, while in CP the reverse was found. The crackers with 20% of AP and CP had a thinner structure (showing a higher spread ratio), which led to lower resistance to breakage, as also described by some other authors for *P. tricornutum* crackers [35,61]. In the case of AP and CP 40%, the addition of water in the recipe to develop a desired cracker resulted in a higher hardness and toughness and less brittleness (Figure 8).

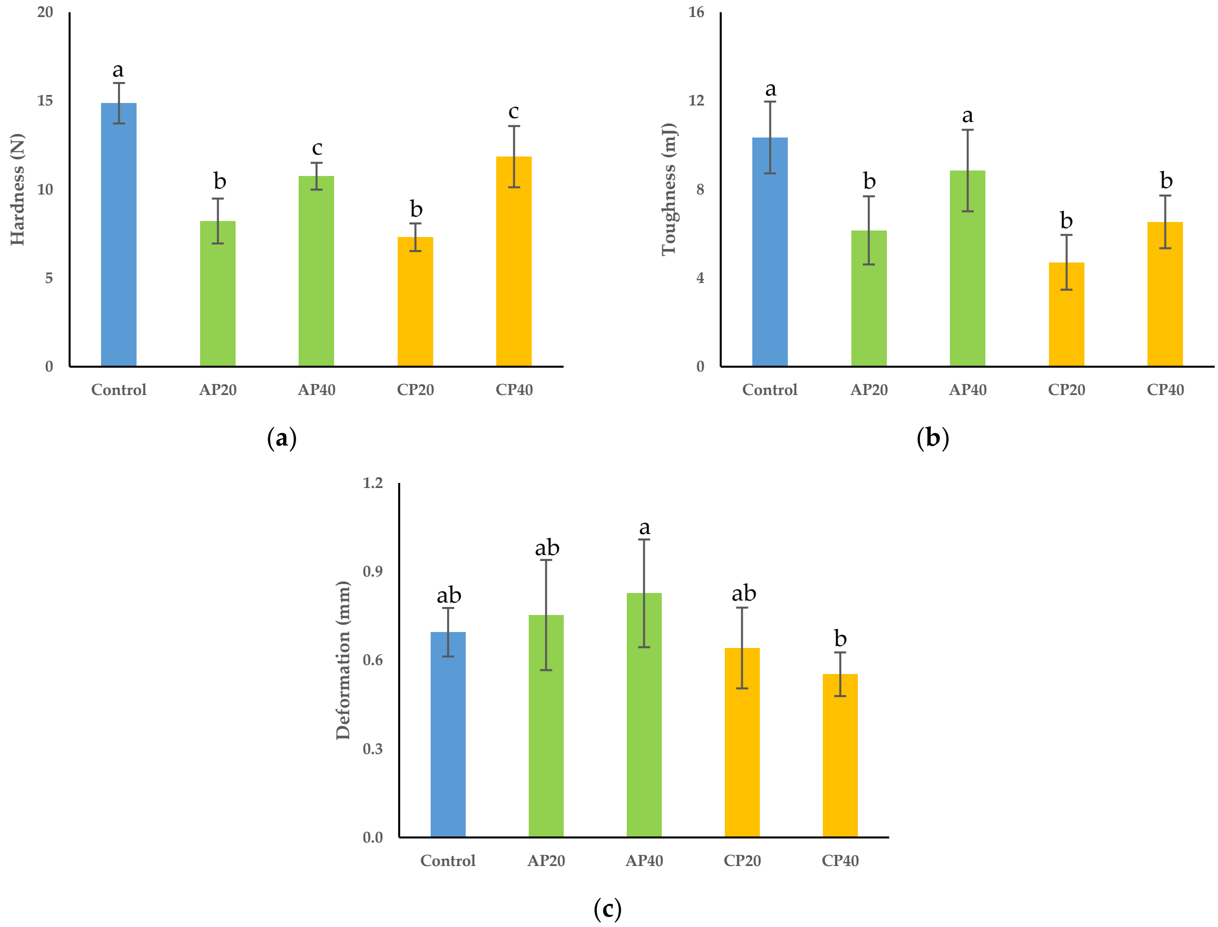


Figure 8. The results of texture parameters of crackers: (**a**) hardness, (**b**) toughness, and (**c**) deformation. Results are expressed as average ± standard deviation (n = 10), followed by an alphabet letter. Different letters mean significantly different results (Tukey's HSD; $p \leq 0.05$).

3.7. Sensory Evaluation

Sensory analysis trials were carried out on samples with 20 and 40% AP and CP pomace flours and the control. Figure 9 represents the average scores of the sensorial parameters, as evaluated by the panel.

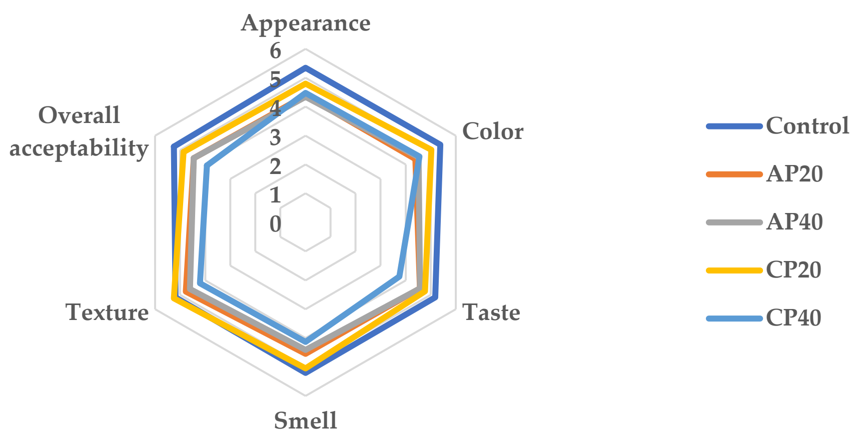


Figure 9. Responses of the sensory analysis panel tasters (n = 44) regarding crackers. Sensory attributes were classified as follows: 1—dislike very much, 2—dislike moderately, 3—dislike slightly, 4—like slightly, 5—like moderately, 6—like very much.

The control sample showed high global sensory scores (>5) and was preferred over the crackers with pomace flours, which was as expected for this amount of pomace flour included. Better sensorial scores (>5) that were even higher than the control were presented by the texture of the crackers with 20% CP, which could be related to the instrumental texture and aw/water content results, indicating a crisp texture [35]. The CP20 was preferred, considering all the parameters evaluated, while crackers with 40% CP showed the lowest scores for taste, smell, texture, and overall acceptability due to their softer texture.

More than 70% of the panelists agreed that crackers with 20% CP received the highest sensory ratings and said that they would probably or definitely purchase this product (Figure 10).

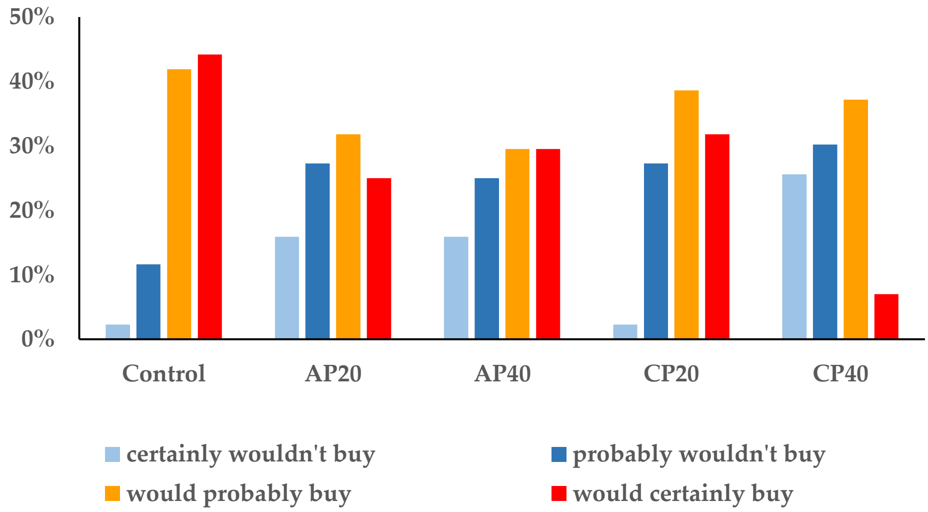


Figure 10. Responses of the sensory analysis panel tasters (n = 44) in terms of buying intention for crackers.

3.8. Total Phenolic Content (TPC) and Antioxidant Potential

The TPC was evaluated on the ethanolic extracts of crackers, as shown in Figure 11. The TPC found in all the crackers' formulation was significantly different ($p > 0.05$) when compared to the control crackers (1.2 mg GAE g^{-1}), except for the CP20 formulation, showing a TPC similar to the one found in the control. This might be due to the lower TPC and antioxidant activity found in the carrot pomace flour used in the preparation [62]. When increasing pomace flour content from 20 to 40% the TPC significantly increased from 3.7 to 4.2 mg GAE g^{-1} ($p < 0.05$) when using apple pomace flour and from 1.9 to 3.5 mg GAE g^{-1} when using carrot pomace flour.

The antioxidant capacity of the crackers was determined using the DPPH and FRAP methods (Figure 12). All the crackers prepared with the two pomace flours showed higher antioxidant potential when compared to the control. Also, apple pomace promoted an improvement in the antioxidant potential when compared with the carrot pomace. It is also evident that upon increasing the amount of pomace flour that was incorporated in the crackers from 20% to 40% an improvement in the antioxidant potential of the crackers was achieved.

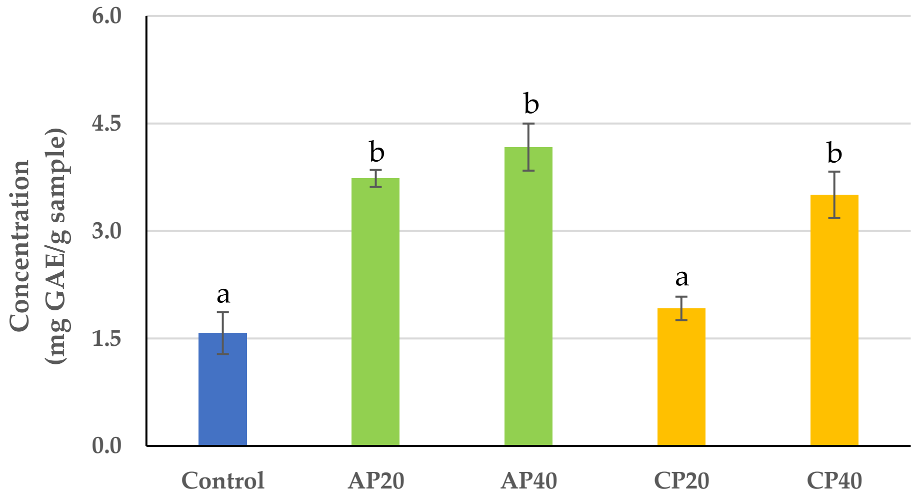


Figure 11. Total phenolic content of crackers, expressed as mg GAE/g sample. Results are expressed as average ± standard deviation (n = 3), followed by an alphabet letter. Different letters mean significantly different results (Tukey's HSD; $p \leq 0.05$).

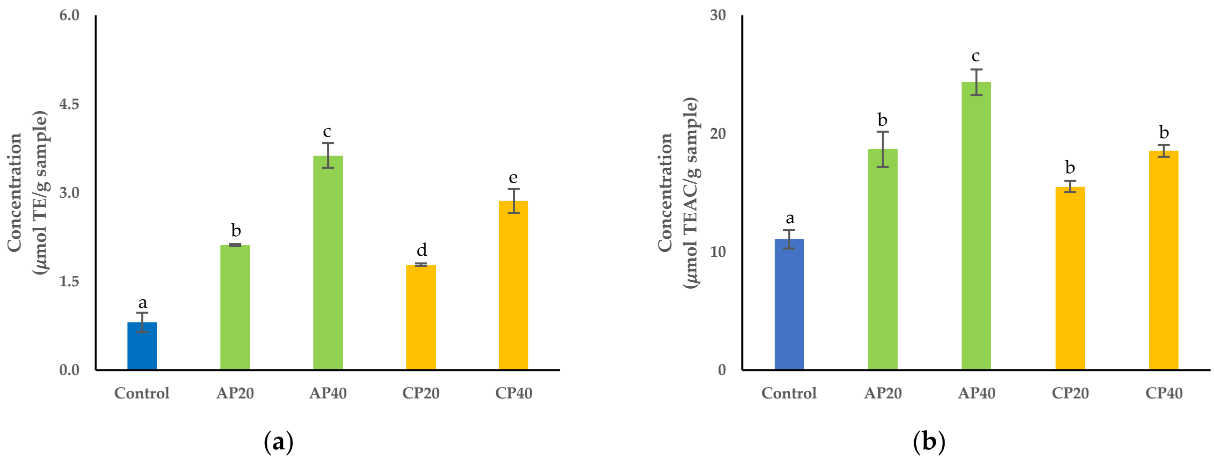


Figure 12. AAT of crackers, measured by DPPH (**a**) and FRAP (**b**), expressed as µmol TE/g sample. Results are expressed as average ± standard deviation (n = 3), followed by an alphabet letter. Different letters mean significantly different results (Tukey's HSD; $p \leq 0.05$).

4. Conclusions

The study's results indicate that adding apple and carrot pomaces to wheat crackers enhanced their total phenolic content and antioxidant activity. The fiber content, especially in AP40 and CP40 variants, improved the dough's rheological properties and the crackers' texture, increasing hardness and brittleness. The sensory analysis results revealed that these texture changes, except for CP40, were well received by the panelists. Among the variants, CP20 emerged as the most preferred cracker, resembling the control in taste and buying intention. Conversely, CP40 had the lowest buying intention, largely due to its bitterness, likely resulting from the carrot residues post-juice extraction.

The incorporation of apple and carrot pomaces in staple foods like crackers is a sustainable way to introduce these residues back into the food chain, adding them as ingredients for food fortification with potential health benefits.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16145995/s1. Here is the caption of S1. Table S1: Minerals composition determined by ICP-EOS for apple and carrot pomace flours. The results are the mean of triplicates shown as mean ± standard deviation (n = 3) and were reported as mg of mineral per 100 g of pomace flour.

Author Contributions: Conceptualization, J.F., A.L. and I.S.; methodology, J.F., A.L. and I.S.; validation, J.F., A.L. and I.S.; formal analysis, S.S., T.C., J.F., A.L. and I.S.; investigation, S.S. and T.C.; data curation, S.S., T.C. and J.F.; writing—original draft preparation, S.S., T.C. and J.F.; writing—review and editing, J.F., A.L. and I.S.; visualization, J.F., A.L. and I.S.; supervision, J.F., A.L. and I.S.; project administration, J.F. and I.S.; funding acquisition, I.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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