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Evaluation of the Chemical Properties of Tomato Products Enriched with Plant-Based Ingredients

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Abstract

Reformulating tomato-based products with beneficial plant-based ingredients is a promising approach for enhancing dietary quality. In this study, the chemical properties of reformulated tomato products—a juice and a sauce enriched with pea protein, olive powder, and tomato peel powder—were evaluated alongside the tomatoes used as raw material (cultivar 'H1657') to determine the changes occurring during their conversion into reformulated products. The chemical properties were assessed by analyzing lycopene, antioxidant capacity (by total phenolic content, DPPH, ABTS, and FRAP), sugars (glucose, fructose, and sucrose), and organic acids (citric, malic, ascorbic, and oxalic acids). The results showed that the fruit had the highest contents of glucose and fructose. Citric, malic, and oxalic acids were lower in the reformulated products than in the fruit sample, while ascorbic acid did not differ significantly. The sauce and fresh fruit exhibited the highest lycopene, ABTS, DPPH, and FRAP, whereas the juice had the lowest. Polyphenol content was highest in the sauce followed by the fruit and then the juice. The results suggest that incorporating plant-based ingredients into the sauce formulation can help compensate for nutrient losses that occur during tomato processing, making it a promising tomato-based product.

Keywords: *Solanum lycopersicum*; tomato juice; tomato sauce; bioactive compounds; lycopene; phenolics content

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1. Introduction

Food reformulation is the process of redesigning processed foods to enhance their health benefits without compromising their nutritional qualities and shelf life [1,2]. Reformulation also responds to evolving consumer preferences and government regulations [3]. One potential strategy is to develop products with a higher content of bioactive components. Bioactive compounds are naturally occurring substances in fruits and vegetables that are recognized for their health benefits. Consequently, individuals worldwide are willing to increase their intake of these compounds. Among the various bioactive substances,

carotenoids, polyphenolics, and ascorbic acid are the most significant [4]. Bioactive food constituents are known to lower the risk of infection, osteoporosis, cardiovascular diseases, cancer, and macular degeneration, primarily due to their antioxidant properties [5].

Tomatoes are globally recognized as one of the most important dietary sources of bioactive compounds that confer health-promoting properties to the fresh fruit and processed tomato products [6]. The consumption of tomato products has been associated with antioxidant, anti-inflammatory, cardioprotective, and chemopreventive effects, mainly due to the presence of lycopene [7]. Since tomatoes are widely consumed fresh or in processed food products such as sauce, juice, ketchup, pulp, puree, and paste [8], there is a great possibility in using tomatoes to formulate new products with increased bioactivity. Incorporating additional nutrients from beneficial components, such as plant-based ingredients, can further enhance the nutritional value of food products [9].

Pea protein is gaining popularity as a new plant-based protein source in the food industry, owing to its availability, cost-effectiveness, and nutritional and health benefits [10]. It is a high-quality protein source with a well-balanced amino acid profile that can fulfill the protein and amino acid requirements set by FAO/WHO [11]. Pea protein contains significant quantities of all essential amino acids. Lysine is notably abundant, while methionine and cysteine act as limiting amino acids [12]. Pea protein has health benefits such as antioxidant and antihypertensive properties and regulating intestinal flora activity [13]. Incorporating pea protein into staple foods offers an opportunity to increase the protein content in diets while simultaneously providing techno-functional properties (i.e., binder, emulsifier, stabilizer, or extender) to the developed product [14]. Protein-fortified tomato products can be an affordable and environmentally sustainable protein source compared to seafood, livestock, and poultry [9]. Similar to tomatoes, olives possess phenolic antioxidants that help in the prevention of chronic illnesses (e.g., cancer and cardiovascular diseases) [15].

Tomato peel represents a major by-product of the tomato processing industry and is particularly rich in lycopene, dietary fiber, and phenolic compounds linked to a lower risk of chronic diseases. Its incorporation into food formulations aligns with circular economy principles and sustainable food production [16]. The presence of different ingredients in complex tomato product formulations can affect their final quality depending on the types, properties, and quantities of the added ingredients [8]. Therefore, the integration of these ingredients into tomato-based matrices may modify physicochemical properties and consequently impact the antioxidant properties and health benefits of the final products.

The objective of the Functionalized Tomato Products (FunTomP https://funtomp.com/, accessed on 20 January 2026) project under which the present study was conducted is to reformulate traditional Mediterranean tomato products, using plant-based proteins (by-products of sugar beet processing and pea protein) and olive powder. During the FunTomP project, mixture design studies [17] were carried out to obtain the best proportion of the ingredients to be combined for each formulation used in this study. The importance of investigating the effect of formulation and preparation techniques on the bioactive compounds and nutritional quality of products was previously highlighted [4]. Therefore, this study evaluated nutritional quality parameters of reformulated tomato juice and sauce enriched with freeze-dried olive powder, pea protein isolate, and tomato peel powder. For this purpose, sugars, organic acids, antioxidant activity, total phenolics, and lycopene content were measured to determine their levels in the developed products relative to the fresh tomato fruit. Overall, the results aimed to provide information on lycopene, total phenolic content, antioxidant activity, organic acids, and sugars in the developed products relative to the fresh tomato fruit used in their preparation.

2. Materials and Methods

2.1. Ingredients

Fresh tomatoes (*Solanum lycopersicum* L. cv. 'H1657' VHL®) were purchased from tomato growers in Ribatejo, Portugal (39°06′00″ N, 8°42′40″ W and average altitude of 20 m above sea level). The 'H1657' VHL® tomato (HeinzSeed Company, Stockton, CA, USA) is a hybrid, ground-culture type that was selected in this study because it produces firm, deep-red-colored fruits and high lycopene levels [18]. In the processing laboratory of the Instituto Superior de Engenharia at the Universidade do Algarve, tomato peels were oven-dried at 50 °C for 24 h and milled into a powder. Homogenized brine-cured green olives were freeze-dried to produce olive powder as described in [19]. Pea protein isolate (>80% protein) was supplied by Vegrano (Başakşehir, Istanbul, Turkey), and kitchen salt was purchased from a local supermarket.

2.2. Reagents and Materials

Ethanol (96%, analytical grade), Folin–Ciocalteu reagent, sodium carbonate (Na_2CO_3), sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), gallic acid, (±)-6-Hydroxy-2,5,7,8-tetramethylchromane-2-carboxylic acid (Trolox), 2,2-azinobis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS•+), 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,4,6-tris(2-pyridyl) S-Triazine (TPTZ), sodium acetate trihydrate ($C_2H_3NaO_2 \cdot 3H_2O$), ferric chloride ($FeCl_3$), glacial acetic acid, ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$), ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$), potassium persulfate, methanol CHROMASOLV™ (high-performance liquid chromatography (HPLC) grade), acetonitrile (HPLC grade), n-hexane (HPLC grade), ethanol absolute (≥99.8%, HPLC grade), dichloromethane (HPLC grade), and lycopene standard (≥98%, HPLC) were obtained from Sigma-Aldrich (Saint Louis, MI, USA). Methyl tert-butyl ether (MTBE) CHROMASOLV™ (≥99.8%, HPLC) was acquired from Honeywell (Charlotte, NC, USA). H_2SO_4 98%, for HPLC LiChropur™, was acquired from Merck KGaA, Darmstadt, Germany.

2.3. Preparation of Tomato Products

The formulation was prepared based on the method proposed by Tchonkouang et al. [17]. The sieved pulp of the ripe tomatoes (without seeds and peels), previously thawed at room temperature (25 °C), underwent a hot-break procedure at 85 °C for reformulated sauce production. Per 100 g of reformulated sauce, there was 93.06 g of hot-break pulp, 3.47 g of tomato peel powder, 1.82 g of pea protein, and 1.66 g of olive powder. For the juice production, the pulp was subjected to a cold break at 65 °C. A portion of the cold-break pulp was centrifuged at 3735.5 g for 5 min (Megastar 1.6R, VWR International BV, Leuven, Belgium), and the supernatant (liquid extract of the pulp called 'tomato serum') was reserved. For each 100 g of reformulated juice, 26 g of cold-break pulp, 70 g of pulp extract, 1 g of tomato peel powder, 1 g of pea protein, 1 g of olive powder, and 1 g of salt were added. These mixtures were then homogenized in a high-pressure homogenizer (HPH) (PandaPlus 2000, GEA, Parma, Italy) at 200 to 500 bars for the sauce and 50 to 100 bars for the juice to obtain homogeneous products. The samples were stored at 4 °C for further analysis. The whole tomato fruit, containing seeds and peels, was homogenized using a kitchen blender (Moulinex 750 W, Ecully, France). The fruit homogenate was analyzed simultaneously to study the effect of including various components in the reformulated products.

2.4. Total Phenolic Content and Antioxidant Activity

Approximately 2 g of sample (i.e., fruit, juice, or sauce) was extracted with 15 mL of ethanol (70%), which was next centrifuged at 4611.75 g for 5 min (Megastar 1.6R, VWR

International BV, Leuven, Belgium). The supernatant was analyzed for antioxidant activity (using ABTS, DPPH, and FRAP methods) and total phenolic content.

The total phenolic content evaluation was based on the spectrophotometric method described in [17]. For each sample, a mixture of 200 µL of ethanolic extract, 1000 µL of Folin–Ciocalteu solution (90%, *v*/*v*), and 800 µL of aqueous sodium carbonate (7.5%, *w*/*v*) was prepared in this order. After resting in the dark for 30 min, the absorbance of the samples was measured at 765 nm using a spectrophotometer (Shimadzu model UV-160A, Shimadzu Corporation, Kyoto, Japan), with the phenolic content results expressed in milligrams of gallic acid equivalents (GAE) per 100 g (mg GAE/100 g) using a gallic acid (0–100 µg/mL) calibration curve.

The determination of antioxidant activity using the DPPH free-radical-scavenging method was carried out according to Brand-Williams et al. [20] with minor modifications. A 25 mg/L solution of DPPH was prepared in ethanol. Briefly, 150 µL of sample or ethanol (control) was added to the same volume (1850 µL) of the ethanolic solution of DPPH. This was followed by a 30 min incubation in the dark at room temperature. The absorbance was measured at 515 nm using a UV-vis spectrophotometer (Shimadzu model UV-160A, Shimadzu Corporation, Kyoto, Japan). The antioxidant activity was calculated as the percentage of radical scavenging activity (RSA%) according to Equation (1):

$$\text{RSA\%} = \frac{(A_0 - A_1)}{A_0 \times 100} \quad (1)$$

where A_0 corresponds to the absorbance of the control and A_1 is the sample absorbance.

A calibration curve with Trolox standards (0–250 µM) was generated and used to estimate the concentration in µmol/100 g Trolox equivalents (µmol/100 g TE) corresponding to the calculated RSA% for each sample.

The radical-scavenging activity against the ABTS•+ cation was determined using a method described by [17]. Potassium persulphate (2.47 mM) and ABTS•+ (7 mM) were mixed and kept at room temperature in a dark environment for 16 h to produce ABTS•+. The ABTS•+ was diluted in ethanol 96% to obtain an absorbance of 0.70–0.80 at 735 nm. An aliquot of 20 µL of sample extract was added to 1980 µL of the cation solution. After 6 min of incubation at room temperature, decolorization resulting from cation reduction by the sample's antioxidants was measured at 735 nm. ABTS•+ scavenging activity was estimated using a Trolox calibration curve (0–2000 µM) and the results expressed as µmol/100 g TE.

The ferric reducing antioxidant power (FRAP) was performed according to the procedure in [17]. The FRAP reagent was prepared by combining acetate buffer at pH 3.6 (300 mM), TPTZ (10 mM in HCl (40 mM)), and $FeCl_3$ (20 mM in distilled water) in a solution ratio of 10:1:1 (*v*/*v*/*v*), respectively. The FRAP reagent (1200 µL) was mixed with 40 µL of tomato product extract. Sample blanks were prepared simultaneously by mixing 40 µL of each sample with 1200 µL of a reagent blank containing ultrapure water, 20 mM $FeCl_3 \cdot 6H_2O$, and 300 mM acetate buffer in a 10:1:1 (*v*/*v*/*v*) ratio. The samples' absorbances were measured at 593 nm after incubation at 37 °C for 15 min. Standard solutions of $FeSO_4 \cdot 7H_2O$ (0–2000 µM) were used for calibration, and the results were presented as µmol/100 g $FeSO_4 \cdot 7H_2O$ (Fe[II]) equivalent.

2.5. Lycopene Extraction and Quantification

Analyses were performed by HPLC based on the protocol described in [21], using an isocratic separation. Approximately 1 g of sample was extracted in 5 mL of methanol. The extract and methanol were sonicated for 30 s in an ultrasonic bath (Branson 3510, Branson Ultrasonics Corporation, Danbury, CT, USA) and centrifuged at 1760 g for 5 min (Cencom 2, J.P. Selecta, Barcelona, Spain). The supernatant was reserved, and the pellet

was re-extracted with 5 mL of hexane–acetone (1:1, *v*/*v*), mixed, sonicated, and centrifuged for 5 min at 1760 g. The supernatant was added to the reserved supernatant, and 10 mL of ultrapure water was added to the combined supernatants. Then, the upper hexane phase in the supernatant mixture was dried under a nitrogen gas stream. Dried samples were resuspended in 1 mL of ethanol–dichloromethane (1:1, *v*/*v*) and filtered through a PTFE membrane (0.45 µm) followed by the injection of 20 µL into an HPLC system equipped with a diode array detector (DAD) (Jasco MD 2015 Plus, Tokyo, Japan) and a C30 column (3 µm × 150 mm × 4.6 mm) attached to a guard column (Surf C30, InChem, Voisins le Bretonneux, France). The mobile phase used was MTBE, acetonitrile, and methanol (50:15:35, *v*/*v*/*v*) at a flow rate of 0.5 mL/min, and the detection wavelength was set to 200–600 nm. A calibration curve of the absorbance (*y*-axis) versus known concentrations (*x*-axis) of lycopene standard solutions (0–100 µg/mL) was generated, allowing the unknown concentration of the samples to be estimated.

2.6. Organic Acids and Sugars

Organic acids (ascorbic, citric, malic, and oxalic) and sugars were analyzed after extraction, based on the work reported by [22], using an HPLC method described previously [23], with minor modifications on the flow rate (0.6 mL/min) and column temperature (65 °C). Summarizing, after cold extraction of freeze-dried samples (50 ± 0.5 mg) for 5 min in 3 mL of HPLC water, the extract was filtered through a 0.2 µm syringe filter before analysis. Ascorbic, citric, malic, and oxalic acid contents were determined using an HPLC quaternary pump system equipped with a diode array detector (DAD, L-2455, Elite LaChrom series, Hitachi, Japan) with a multiple wavelength detector, degasser, and cooled autosampler. The mobile phase used was 5 mM H_2SO_4 at a flow rate of 0.6 mL/min, with an Aminex HPX-87H ion exclusion column (300 × 7.8 mm), equipped with a guard column packed with a cation-H exchange cartridge (Bio-Rad, Hercules, CA, USA) with the column's temperature set at 65 °C using an external column heater CROCO-CIL (40 cm × 8 cm × 8 cm) (Amchro GmbH, Hattersheim am Main, Germany). The injected filtered sample extract was 20 µL, and the detection wavelength for non-volatile organic acids used was 210 nm. To estimate organic acid concentrations, a calibration curve was plotted for each acid using standard solutions with concentrations from 0.15 to 2.5 mg/mL for ascorbic, citric, and malic acids and from 0.06 to 1 mg/mL for oxalic acid.

HPLC quantification of sugars (sucrose, glucose, and fructose) was based on a method described by [23], with minor modifications on the flow rate and column temperature. Briefly, 3 mL of 62.5% (*v*/*v*) aqueous methanol was added to 150 ± 0.5 mg of lyophilized sample to extract the sugars. The concentrations of fructose, glucose, and sucrose in the extracts were determined using an HPLC binary pump system (L-2130, Elite LaChrom series, Hitachi, Japan). A small volume (20 µL) of a diluted sample (1:10) was injected into an Aminex HPX-87H ion exclusion column (300 × 7.8 mm), equipped with a guard column packed with a cation-H exchange cartridge (Bio-Rad, Hercules, CA, USA). The thermostatic column compartment temperature was set at 65 °C. The mobile phase was 5 mM H_2SO_4 at a flow rate of 0.6 mL/min, and carbohydrates were detected using a refractive index detector (RID, L-2490, Elite LaChrom series, Hitachi, Japan). The analyzed sugars were quantified using a linear calibration curve made with standard solutions of 1, 2, 5, 10, and 25 mg/mL.

2.7. Statistical Analysis

One-way analysis of variance (ANOVA) followed by the post hoc Tukey's multiple comparison test was conducted using the software SPSS (version 29.0.2.0) to assess differences between sample groups with a significance level of 0.05 (α) and expressing the

results as average ± standard deviation (SD) of three independent experiments. Moreover, a principal component analysis (PCA) was performed in R Studio (version 2025.5.1.51, Integrated Development for R. Posit Software, PBC, Boston, MA, USA) using the FactoMineR package (version 2.12) [24], and the corresponding PCA biplot was generated with the Factoextra package (version 1.0.7) [25] to visualize the relationships between variables and sample grouping.

3. Results and Discussion

3.1. Total Phenolic Content, Antioxidant Activity, and Lycopene

The total phenolic content (TPC) detected in tomato fruit, reformulated tomato juice, and reformulated tomato sauce is presented in Figure 1. The TPC ranged between 42.71 ± 5.72 mg GAE/100 g (juice) and 100.69 ± 4.07 mg GAE/100 g (sauce), and the sauce, found to have the highest TPC, was statistically different at $p < 0.05$. Previous studies in tomato sauces [26] and tomato sofrito [27] showed that ingredient variations cause differences in TPC content. The skin and seeds of tomatoes are richer sources of polyphenolic compounds than the pulp [28]. The peels and seeds from two Spanish cultivars (Murcia and Almeria) contained a wide variety of polyphenolic compounds, including twelve hydroxybenzoic acids and 18 hydroxycinnamic acids [29]. Chabi et al. [30] estimated a TPC of 4.8 mg/100 g in tomato seed meal. Hence, the presence of seeds in the fruit contributed to the sauce's total phenolic content, and adding more tomato peel powder increased the sauce's phenolic content. The addition of olive powder to the matrix can enhance the TPC. Olive fruits are abundant in PCs that function as primary antioxidants in olive extracts [31]. The study by Sahan et al. [32] indicated the high TPC content in olives, with a TPC content of approximately 15,000 mg GAE/100 g in raw green olives. Also, a higher tomato pulp weight can contribute positively to TPC. TPC in sauce with 100% tomato pulp (62.95 ± 1.64 µg GAE/g) was higher than 50% tomato + 50% pumpkin sauce [4].

The presence of pea protein in the formulation could contribute to the TPC. Pea protein had a TPC of approximately 0.9 mg GAE/g in the experiment conducted by Sawicki et al. [33]. The main interaction partners of phenolic compounds (PCs) in PC-rich foods are proteins, which provide several structural features that enable covalent and non-covalent interactions with PCs. These interactions can positively or negatively affect the final TPC of food [34]. For instance, tomato sauce enriched with 5 g of *Chlorella vulgaris* protein isolate had a lower polyphenol content than tomato sauce enriched with 1 g of protein isolate [35], suggesting that numerous interactions can occur between proteins and PCs, making it challenging to predict outcomes in complex food matrices.

The antioxidant activity (AA) of the samples, as measured by DPPH, showed significant differences between the juice and the sauce, and the fruit and the juice (Figure 1b). The same applies to the FRAP test (Figure 1d). However, the ABTS test had a significant difference ($p < 0.05$) only between the juice and the sauce (Figure 1c). The antioxidant analyses revealed that both the fruit and sauce demonstrated higher free-radical-scavenging activity than the juice. This is consistent with the observed higher TPC of the fruit and sauce. Phenolic compounds are effective scavengers of free radicals, and numerous potential health benefits have been attributed to their presence [28]. Damak et al. [36] reported that the concentration of phenolics such as hydroxytyrosol and oleuropein was related to the capacity of free radical inhibition in AA measurement. In another study, extracts with higher phenolic compounds exhibited higher AA [37]. Similarly, a research study on tomato peels and seeds highlighted that the TPC and AA (analyzed by DPPH and FRAP) in the peels of the 'Petomech' and 'F1 Mongal' tomato cultivars were greater than in the seeds. The higher AA may be linked to the presence of antioxidants, including phenolics, carotenoids, and ascorbic acid [38]. A study that examined the effects of incorporating

dried tomato peel and seeds in fresh acid cheese production concluded that peels and seeds are important sources of PCs and antioxidants. Inclusion of 5% tomato seeds and peel in cheese resulted in the highest AA, TPC, and flavonoid content [39].

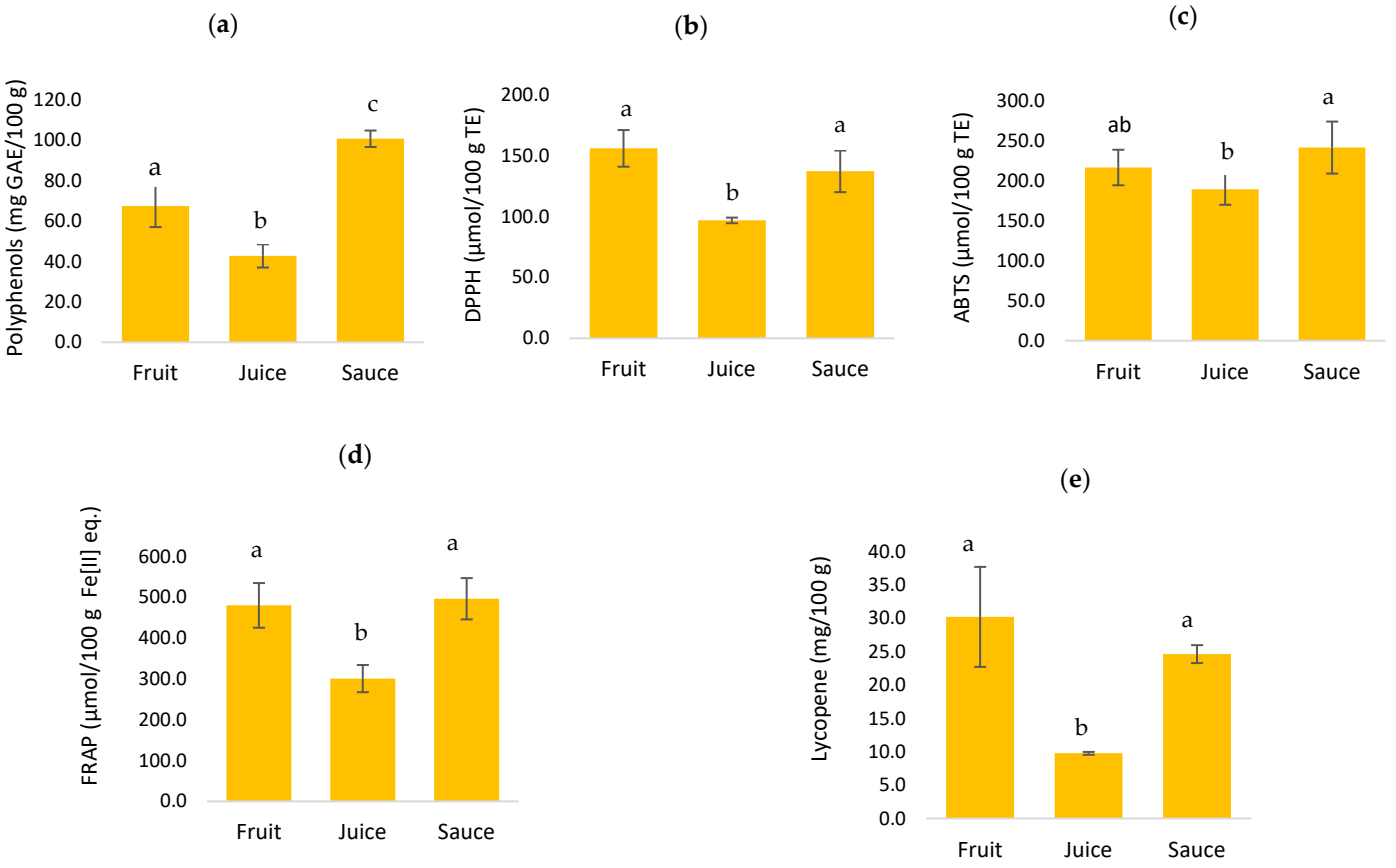

Figure 1. Mean lycopene, phenolic content, and antioxidant activity of tomato fruit, sauce, and juice: (**a**) Polyphenols (mg GAE/ 100 g); (**b**) DPPH (µmol/100 g TE); (**c**) ABTS (µmol/100 g TE); (**d**) FRAP (µmol/100 g Fe[II] eq.); (**e**) Lycopene (mg/100 g). Same letters indicate no significant differences, and different letters indicate that the mean differences between sample groups are significant, as determined by one-way ANOVA and the Tukey HSD test ($p < 0.05$). Error bars represent standard deviations.

It has been shown that pea protein isolates possess AA. The AA of pea protein examined using the ABTS assay was 1.95 ± 0.04 µmol TE/g [33]. Two grades of pea protein isolates, NUTRALYS® S85F and NUTRALYS® S85 Plus, showed significant scavenging activities against H_2O_2 and HO radicals before and after in vitro gastro-intestinal digestion and, as a result, may provide oxidative stability to food products and health benefits to consumers [40]. The interaction between dietary proteins and PCs has promising effects on the antioxidant properties of foods. Previous research showed that dietary proteins exhibit higher antioxidant activities after complexation with PCs [41]. Coatings were produced by incorporating a 5% phenolic extract from apple pomace into a 10% aqueous solution of pea protein. Hazelnuts coated with this solution had an antioxidant activity ~2.5 times higher (ABTS) and 30 times higher (DPPH) than the uncoated samples [42]. The PC–protein interaction between malvidin-3-O-galactoside and whey protein isolate (involving hydrophobic interactions and hydrogen bonding) enhanced the retention rate of blueberry anthocyanin during a simulated in vitro digestion, leading to improved antioxidant activity [43]. Additionally, yoghurts enriched with hot-break tomato powders had greater AA and TPC than those with cold-break tomato powders because of the stimulating effect of heat treatment on phenolic components [44]. Hence, the significantly higher polyphenols of the sauce

compared to the juice could potentially be related to the hot-break pre-treatment of the sauce. Based on our findings, all antioxidant assays indicate that the fruit and sauce have higher AA than the juice. The separation of serum from the pulp, the more diluted nature of the juice, and the interaction of the ingredients within the juice matrix could be responsible for its lower TPC and AA.

The antioxidant capacity of tomatoes and tomato products is attributed mainly to their lycopene content [45]. Lycopene levels in a tomato cultivar and its processed products may vary with the harvest time, type of processing, processing conditions, presence of other ingredients, and extraction method [46,47]. The highest lycopene concentration was obtained in the fruits (30.22 ± 7.50 mg/100 g), followed by the sauce (24.63 ± 1.34 mg/100 g) and the juice (9.77 ± 0.22 mg/100 g); however, the difference between the sauce and fruit was non-significant (Figure 1e). The lycopene concentration of the fresh tomato is higher than values obtained in studies performed by other scientists, who found that the lycopene content of tomatoes was approximately 12 mg/100 g and 13.6 mg/100 g [48]. Traditional tomatoes analyzed by Li et al. [49] in a recent study also had lower lycopene concentrations varying from 0.94 to 6.81 mg/100 g. The fruit's average lycopene (30.22 mg/100 g) in this study is close to the lycopene content (38.88 mg/100 g) of tomato paste [46]. Based on the results, tomato H1657 is a reliable source of lycopene. It has been reported that processing tomato cultivars classified as 'high-pigment or high-lycopene' (e.g., cvs. Gochiso PR-7, H1311, H1657, BRS Tospodoro, and Kalvert) can accumulate more lycopene than traditional tomatoes [50–52]. Recorded lycopene concentrations of other high-lycopene cultivars at the red-ripe stage include 23.29 mg/100 g FW in HLY18, and 20.8 mg/100 g FW in tomato genotypes possessing the high-pigment mutation hp-2dg [53]. Other high-lycopene cultivars had lower lycopene of 15 mg/100 g to 16.7 mg/100 g in 'Kalvert' [54], 19.8 mg/100 g FW in 'VHL® H1311', and 17.79 mg/100 g FW in 'HLY13' [53].

The lycopene results followed the same tendency as the AA and TPC results, with higher lycopene concentration in fruit and sauce. These results show that the different ingredient quantities impacted the lycopene levels in the juice and sauce. Incorporating tomato peel powder in food products has been demonstrated to increase the lycopene content significantly [55,56]. Another study reported that the peel-rich fraction of tomato by-product contained a higher lycopene level than the seed-rich fraction [57]. The peel was found to contain 3.5 to 3.75 times more lycopene than the pulp of the same tomatoes [58]. Moreover, a higher pulp percentage in the sauce could have positively influenced the lycopene concentration. Total carotenoids of sauces increased with increased tomato pulp amount in a previous study. Sauces with 100% tomato pulp and 75% tomato pulp + 25% pumpkin had higher lycopene than the sauce with 50% tomato pulp + 50% pumpkin [4]. Increasing the proportions of olive powder and protein was seen to improve the lycopene content in tomato products [59]. Adding olive oil increased the concentrations of cis- and trans-lycopene in tomato sauces [60], and adding corn and olive oils increased the amount of lycopene released from the tomato matrix [61]. Olive powder contributes to increased lycopene because lycopene's availability increases in the presence of lipids due to its hydrophobicity [62]. Researchers previously indicated that protein addition positively influenced both carotenoid bioaccessibility and availability in tomato juice [63]. The lycopene level of the sauce (24.63 ± 1.34 mg/100 g), which was comparable to the lycopene content of the fresh tomatoes (30.22 ± 7.50 mg/100 g), was therefore positively impacted by the greater pulp, peel powder, olive powder, and pea protein amounts in the sauce.

However, the absence of seeds negatively affects lycopene and antioxidant activity. According to Chabi et al. [30], seeds are the most nutrient-dense component in tomatoes and are highly abundant in carotenoids (with 43.65 μg/g of lycopene and 23.62 μg/g

of β-carotene). Pizzolongo et al. [64] reported that whole tomato puree (pulp + seed + peels) showed improved antioxidant capacity compared to traditional puree (pulp with traces of seeds and peels), due to β-carotene and polyphenols found in the seeds and peels. Overall, the obtained results revealed that the sauce's formulation could compensate for the losses incurred during the processing of fresh tomatoes into sauce, thereby preserving the bioactive compounds.

3.2. Sugars and Organic Acids

Sugars and organic acids are essential constituents that contribute to the sweet and sour taste of tomatoes, respectively. Variations in their concentrations strongly influence the sensory acceptability [65]. The results of the soluble sugars, which include fructose, glucose, and sucrose, are shown in Table 1. Sugar content is associated with consumer preferences, with most consumers preferring sweeter products [66]. For most tomato cultivars, glucose and fructose are the dominant soluble sugars in ripe fruits [67]. The analysis revealed very low sucrose levels relative to the other sugars, with no significant difference in sucrose content ($p < 0.05$). This aligns with the expected findings, given the typically low levels of this sugar in red-ripe tomatoes [68].

Table 1. Average sugar and organic acid content of tomato fruit, sauce, and juice. Same letters indicate no significant differences, and different letters indicate that the mean differences between sample groups are significant, as determined by one-way ANOVA and Tukey's HSD test ($p < 0.05$).

Parameters (mg/g DW)	Tomato Fruit	Juice	Sauce
Sucrose	43.4 ± 7.9 ^{a}	35.6 ± 7.8 ^{a}	35.7 ± 9.8 ^{a}
Glucose	215.2 ± 42.7 ^{a}	121.9 ± 9.8 ^{b}	118.3 ± 11.9 ^{b}
Fructose	348.5 ± 79.3 ^{a}	179.1 ± 20.5 ^{b}	198.1 ± 24.3 ^{b}
Ascorbic acid	65.8 ± 3.7 ^{a}	61.8 ± 7.5 ^{a}	57.3 ± 2.6 ^{a}
Citric acid	104.0 ± 18.6 ^{a}	81.1 ± 5.0 ^{b}	69.6 ± 4.6 ^{b}
Malic acid	69.6 ± 5.1 ^{a}	49.1 ± 5.0 ^{b}	37.1 ± 2.4 ^{c}
Oxalic acid	18.4 ± 0.1 ^{a}	17.8 ± 0.1 ^{b}	17.8 ± 0.0 ^{b}

The whole fruit samples had the highest glucose and sucrose levels, and no significant differences were found between the juice and the sauce. Previous research reported that the break temperature did not affect the soluble sugar content of canned juices made from 'UC82B' tomatoes [69]. In cheese formulations containing pea protein concentrates, samples with higher protein content had lower sugar content [70]. Furthermore, researchers observed that a higher concentration of sugar solution resulted in a lower protein content in tomato candies, while a lower concentration of sugar solution led to a higher protein content. The protein content of tomato candy with a 40% sugar solution was 2.97%, and a progressive decrease from 2.58% to 2.00% was observed as the sugar concentration increased from 50% to 60% [71]. These findings suggest that an increased protein content might be associated with reduced sugar levels, although studies supporting this observation are limited. For this reason, additional studies are necessary to corroborate these findings and understand the mechanisms that drive these alterations.

The organic acid composition can vary significantly among different tomato cultivars [72]. Table 1 shows the organic acid contents of the samples. Citric, ascorbic, and malic acids were the major organic acids in all samples. The most abundant organic acids in tomatoes are citric acid, followed by malic acid. Additionally, ascorbic acid (vitamin C) is present, but it is not as abundant as malic and citric acids [73]. This statement aligns with our findings because our fruits had the highest concentration of citric acid (104.00 ± 18.57 mg/g

DW), followed by malic (69.55 ± 5.11 mg/g DW), ascorbic (65.81 ± 3.72 mg/g DW), and oxalic acids (18.41 ± 0.12 mg/g DW).

There was no significant difference in the ascorbic acid levels of all samples. Citric and malic acid levels declined in the juice and the sauce supplemented with olive powder and pea protein compared to the fruit ($p < 0.05$). According to Rayman Ergün [74], losses in ascorbic, citric, and malic acids can cause a decrease in titratable acidity. Previous studies showed that the addition of 1–10% fresh purslane leaves to tomato sauces increased the protein content, and these sauces had lower acidity than the sample without purslane [75]. This corroborates our results, in which the observed lower acidity in the juice and sauce could be attributed to the increased protein content resulting from the addition of pea protein. In addition, the significantly lower malic and citric acid levels in the sauce compared to the juice may be attributed to the fact that the sauce was processed by hot-break; this method deactivates pectolytic enzymes, thus producing acidic breakdown products from the pectin molecules [76]. In fact, less titratable acidity was recorded in tomato juice [76] and currant tomato pulp [77] processed by hot-break compared to their counterparts processed by cold-break.

Moreover, the higher content of red tomato peel powder in the sauce could negatively affect the acid content. In a previous study [72], organic acid content was negatively correlated with the green to red hue of the tomato peel. Furthermore, in processed tomato products, the levels of primary acids are altered by the formation and degradation of organic acids, resulting in a change in the organic acid profile [73]. For instance, Marconi et al. [65] analyzed the content of organic acids of various tomato juice samples and found that citric and pyroglutamic acids were predominant.

Although oxalic acid was detected in trace amounts in all samples, measuring oxalic acid in foods is essential because it is widely recognized as an antinutrient that negatively impacts human health. Oxalates limit the bioavailability of some nutrients by binding minerals such as calcium, magnesium, and iron, reducing their absorption and effectiveness [78]. Excessive oxalate intake from oxalate-rich foods can lead to kidney-related disorders, disturbances in glycine metabolism, and lower blood coagulability [79]. The fruit had a slightly higher oxalic acid content (18.41 ± 0.12 mg/g DW) than the juice (17.81 ± 0.08 mg/g DW) and sauce (17.80 ± 0.04 mg/g DW), at a significance level of 0.05. Similarly, oxalic acid decreased in canned tomato juice as the break temperature increased [69]. The difference in the formulation of the juice and sauce did not significantly affect the oxalic acid levels, and the low oxalic acid content of the reformulated tomato products is beneficial for consumers. In general, our results showed no significant differences in the organic acids of the juice and the sauce, except for malic acid. This implies the formulation had little influence on the levels of the analyzed organic acids.

3.3. Principal Component Analysis (PCA)

The PCA biplot shows the distribution of the samples and the contribution of the variables to the first two principal components (Figure 2). It revealed a clear separation among the three sample types (juice, sauce, and fruit), indicating distinct chemical and functional profiles (Dim1 = 63.8%, Dim2 = 36.2%; cumulative variance = 100%). A major contributor to the variability in fruit samples was the presence of glucose, fructose, citric acid, oxalic acid, and sucrose, along with Dim1, which explained most of the variability. In contrast, juice samples were located on the negative side of Dim1 and slightly negative on Dim2, indicating an opposite trend relative to fruit (Figure 2). This suggests a reduced concentration of sugars and organic acids, due to processing, dilution, or loss of solids during juice extraction.

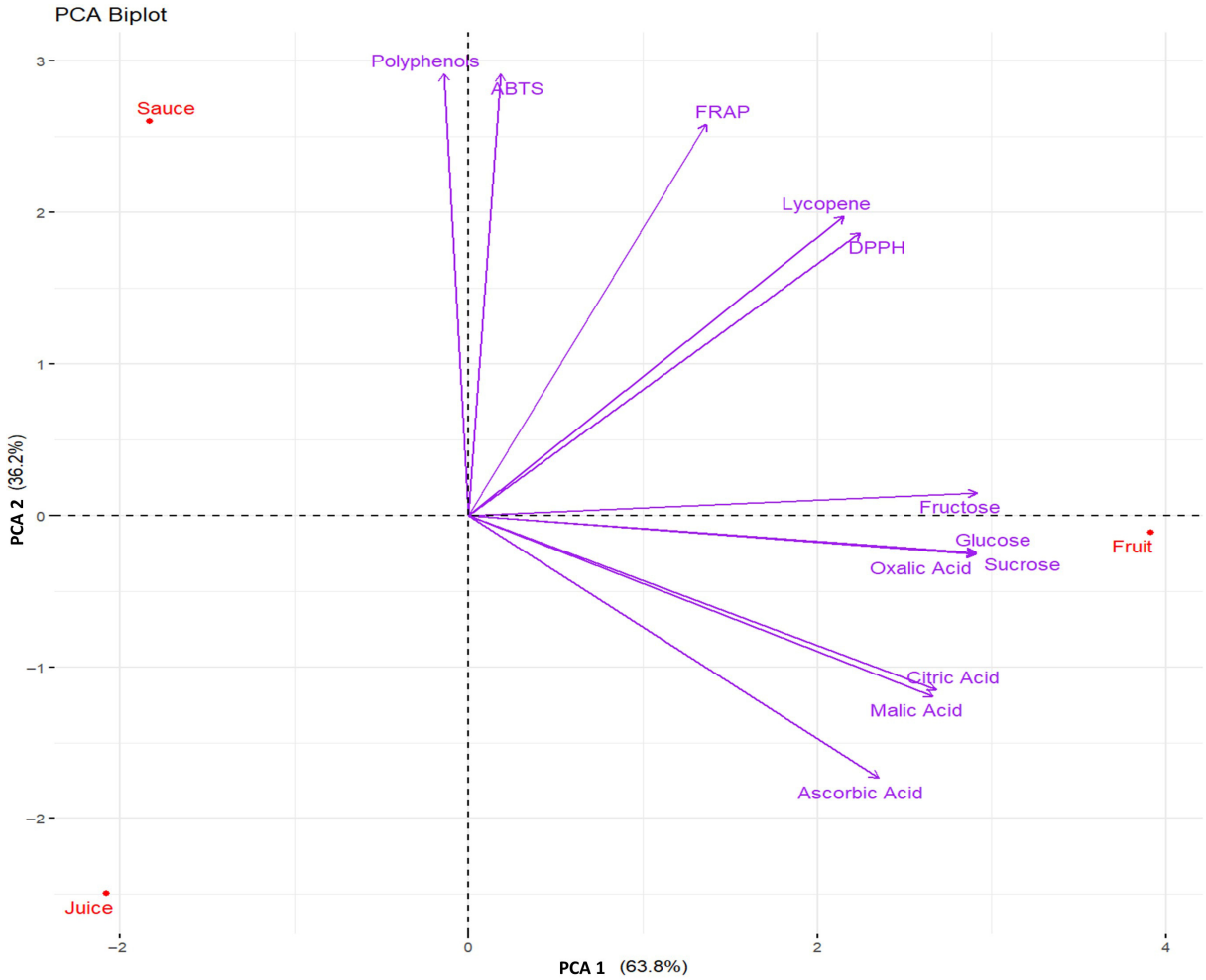

Figure 2. Principal component analysis (PCA) biplot of tomato fruit, juice, and sauce based on chemical properties and antioxidant capacity. The direction and strength of each variable's contribution is indicated by the arrows.

Sauce samples clustered on the positive side of Dim2, separate from both fruit and juice (Figure 2). The sauce was strongly associated with polyphenols, ABTS, FRAP, DPPH, and lycopene, which points out that the sauce formulation has the highest antioxidant potential among the products in the study. This is consistent with typical thermal processing, which can enhance the extractability of carotenoids and phenolics, particularly lycopene [80,81].

The correlation structure of the variables further supports these observations. Antioxidant assays (ABTS, FRAP, and DPPH) were positively correlated with polyphenols and lycopene, suggesting that the antioxidant capacity of the products is driven by these compounds [82]. Conversely, sugars (glucose, fructose, and sucrose) and organic acids (citric, malic, and oxalic) were positively correlated with one another but negatively associated with antioxidant markers, indicating a compositional divergence between nutrient-rich raw fruit and the bioactive-enriched sauce.

The PCA shows a strong differentiation among the product types (Figure 2). Fruit is defined by its intrinsic sugar–acid matrix, sauce by its enriched antioxidant profile, and juice by a reduction in both antioxidant and structural components.

4. Conclusions

Considering the growing health-consciousness among consumers and interest in plant-based foods, this article analyzes the chemical properties of the fresh 'H1657' tomato fruit and its reformulated products (juice and sauce). The AA (by ABTS, DPPH, and FRAP),

TPC content, lycopene, sugars, and organic acids of reformulated tomato products were studied. Based on the results, significantly higher AA, TPC, and lycopene were observed in the fruit and sauce compared to the juice ($p < 0.05$). Variations in composition and different interactions between components within the products' matrices, such as lycopene, phenolic compounds, and protein, could be associated with the observed differences. A decline in sugars (i.e., glucose and fructose) and organic acids (i.e., citric, malic, and oxalic acids) was observed in the reformulated products as compared to fresh fruit, and little variation was observed between the reformulated products (only malic acid showed significant differences between the juice and the sauce). The break temperature might have contributed to the changes in organic acids, while sugars remained unaffected. Given that the sauce's lycopene content and antioxidant capacity (measured via TPC, DPPH, ABTS, and FRAP) were nearly equal to the fresh fruit values, adding bioactive-rich ingredients may compensate for the losses in bioactive compounds incurred during the conversion of the 'H1657' tomato fruit into the reformulated sauce. Further research should investigate the individual contributions of the break temperatures and plant-based ingredients. In addition, including additional controls, such as commercial tomato juice and sauce samples, could provide more insight into the differences in chemical properties.

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