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Comparative Analysis of Phytochemical Composition and Antioxidant Activity of Fresh vs. Processed Fruits

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Abstract: Post harvest processing methods such as thermal treatment, freezing, drying, and industrial canning have a significant impact on the nutritional integrity of fruits. This paper is a systematic review of and comparison of the phytochemical profiles of ten economically and nutritionally important fruit species (both fresh and processed) in terms of total phenolic content (TPC), total flavonoid content (TFC), ascorbic acid, carotenoid levels and anthocyanin content and antioxidant activity. Based on the known in vitro assay protocols such as DPPH, FRAP, and ABTS assays, we compared the effects that different processing modalities have on the bioactive compounds content and functional antioxidant properties differently. Findings indicate that thermal treatment invariably led to a 18-42 percent reduction in TPC and ascorbic acid content by 30-65 percent, and freezing retained more than 85 percent of phytochemicals. Lycopene bioavailability in tomato was enhanced by up to 35% following heat treatment. The highest overall retention rates were with freeze-drying. The implications of these findings include considerable implications to dietary recommendations, food industry processing standards and within the nutritional policy of the population health.

Keywords: Phytochemicals, Antioxidant Activity, Fruit Processing, Total Phenolic Content.

Introduction

The world discourse on the health of food has more and more been unified in the understanding that fruits are one of the most bioactively diverse and nutritionally important classes of foods accessible to human populations. Fruits are rich in vitamins, dietary fiber, minerals, and a wide range of secondary metabolites of plants (also known as phytochemicals) which have been associated with the prevention of non-communicable diseases, such as cardiovascular disease, type 2 diabetes mellitus, and various oncological conditions. The antioxidant activity of the phytochemicals in the fruits is credited with much of the protective effects observed in relation to fruit consumption, and is thought

to neutralize the reactive oxygen species (ROS) and the oxidative stress associated with the pathogenesis of chronic diseases (Martínez-Valverde et al., 2023).

The Phytochemicals found in fruits include a structurally diverse mixture of compounds, such as polyphenols (flavonoids, phenolic acids, tannins, and stilbenes), carotenoid compounds (alpha- and beta-carotene, lycopene, lutein and zeaxanthin), vitamin C, vitamin E and other sulfur based compounds. These bioactive molecules act via several mechanistic pathways, such as direct free radical scavenging, metal ion chelation, enzyme inhibition, and the regulation of cellular signaling cascades, which are related to inflammation and apoptosis (Zhou et al., 2024). It is believed that the synergistic effects of these compounds in entire fruit matrices are key to the observed health-promoting effects, which are usually greater than those that may reasonably be expected based on the activity of individual isolated constituents.

In spite of the health advantages that have been firmly established in the consumption of fresh fruits, a large percentage of the world population still eats fruits in processed products on a regular basis; canned, frozen, and dried fruits, as well as fruit juices and pasteurized fruit products. Processing is an economic and logistical requirement, that extends shelf life, increases geographic availability, lessens food waste and enhances microbial safety. Processing however, has a complex, multifactorial and highly compound-specific effect on phytochemical integrity. It is known that thermolabile compounds (vitamin C, some anthocyanins, etc.) are degraded by thermal treatments but that heat-stable carotenoids (lycopene, etc.) have their bioaccessibility increased by the disruption of cell wall matrices and protein-pigment complexes (Patras et al., 2023).

The body of scientific evidence regarding the impact of food processing on the retention of phytochemicals and antioxidant activity has grown significantly over the past several years, owing to the rising consumer awareness of food quality, and to the growing regulatory concern over the accuracy of the nutrient labels on the packaging. Nevertheless, the current literature often concentrates on either single fruit or fruit species, specific processing techniques, or individual classes of compounds, which limits the comparative

application of the results to nutritional practice and food policy. The elaborate, multi-species, multi-processing-mode study is thus justified to explain general trends and species-specific exceptions.

The research paper discusses the current gaps in the literature due to a systematic comparative study of the phytochemical content and antioxidant activity of ten species of fruits in fresh and various processed conditions. The objectives of the study are: (1) to determine the concentration of important phytochemical classes in fresh and processed fruit samples by validated spectrophotometric and chromatographic methods; (2) to measure the antioxidant activity of the sample using multi-assay method; (3) to determine the processing modality which offers the best phytochemical retention in each fruit species; and (4) to generalize

Literature Review

Phytochemicals in Fruits: Health Significance and Classification

Phytochemicals can be generally described as biologically active non-nutrient compounds of plants with proven health effects at physiologically relevant concentrations. In the framework of fruit science, polyphenols are the most widely researched type of phytochemicals because of their structural diversity, abundance, and wide range of bioactivities. In the epidemiological and clinical literature, the subclass of flavonoid—including flavanols (quercetin, kaempferol), flavanones (hesperidin, naringenin), anthocyanins (cyanidin, delphinidin), flavan-3-ols (catechins, epicatechins), and isoflavones has gained a special interest (Kumar et al., Quercetin, which is found in high amounts in apples and grapes, has also been shown to suppress the activity of xanthine oxidase and cyclo-oxygenase enzymes, and hence oxidative stress and production of inflammatory mediators.

Another important category of polyphenols in fruits is found in the form of phenolic acids, such as hydroxycinnamic (chlorogenic acid, caffeic acid, ferulic acid) and hydroxybenzoic (gallic acid, ellagic acid) acids. Chlorogenic acid (especially blueberries, cherries, and apples) have been linked to enhanced insulin sensitivity, decreased blood pressure, and anti-carcinogenic properties in various test systems (Rodriguez-Perez et al., 2024). Pomegranates, strawberries and raspberries contain ellagic acid and its tannin hydrolysable precursors, which are subject to intestinal biotransformation to urolithins, which have been demonstrated to possess strong anti-inflammatory and mitophagy-promoting effects in clinical studies on humans. Carotenoids are fat soluble yellow-red flavors which give many fruits their characteristic cooler which are the precursors of vitamin A and singlet oxygen and peroxy radical quenchers. The most nutritionally important carotenoids in fruits are beta-carotene, lycopene, lutein, and zeaxanthin, and their dietary intake is epidemiologically associated with lower risk of age-related macular degeneration, prostate cancer, and cardiovascular disease (Oliveira et al., 2024). Ascorbic acid is a water-soluble antioxidant and a necessary cofactor in collagen synthesis, immunology, and non-heme iron absorption, and concentrations of fruits analyzed ranged between 6.3 mg/100 g FW in apple to 228.7 mg/100 g FW in papaya (Chen et al., 2023).

Effects of Thermal Processing on Phytochemical Content

Thermal processing is a collection of industrially and domestically utilized processes such as blanching, pasteurization, sterilization and other cooking methods. Heat influences the fruit phytochemicals in a compound-specific fashion controlled by the Maillard reaction, hydrolysis, oxidation, and redistribution into aqueous and solid phases. An average loss of 20-40% of total phenolics and 30-55% of ascorbic acid due to leaching into blanching water has been reported (Garcia-Parra et al., 2023). It has been shown in the research studies on pasteurization that high-temperature, short-time protocols are less harmful than low-temperature, long-time protocols in preserving polyphenol and the pasteurization of pomegranate juice using the high-temperature, short-time protocol reduced the anthocyanin content of the sample by a factor of 22 (Ahmed et al., 2024). Canning is an extended thermal sterilization process done at temperatures of 100-121 degree C and it produces shelf stable products with significantly modified phytochemical profiles. Comparative studies on fresh and commercially tinned peaches, pears and apricots have shown TPC losses of 25-50, which are correlated with processing temperature and time (Li et al., 2024). The canned products are syrup or juice medium, which can hold a percentage of water-soluble phytochemicals washed out of the fruit tissues, and this will preserve some of the total antioxidant activity when ingested with the liquid.

Non-Thermal Processing and Phytochemical Stability

Freezing is considered to be the most popular non-thermal preservation, and commercial quick-frozen fruits retain 85-98 percent of fresh TPC and 75-95 percent of ascorbic acid content during storage lasting to twelve months (Barba et al., 2023). It is believed that freeze-drying (lyophilization) is the most phytochemically protective drying method with a TPC retention over 90 percent over fresh controls (Wojdyło et al., 2024). Isostatic pressures of 100-600 Mpa (high-pressure processing or HPP) has been shown to be superior to thermal pasteurization in preserving the polyphenol content and antioxidant activity of fruit juices, with strawberry juice at 400 Mpa maintaining 94 percent of anthocyanin content as compared to 71 percent after thermal pasteurization (Ramos et

Antioxidant Assay Methodologies

The combination of DPPH, FRAP, and ABTS systems of assays has a more holistic evaluation of antioxidant capacity than any other single method. The DPPH assay is used to measure hydrogen atom or electron donation to the stable DPPH radical; the FRAP assay is used to measure electron transfer-based reducing capacity; and the ABTS assay is used to measure quenching of the preformed ABTS. + radical cation, which can be used with both hydrophilic and lipophilic antioxidants (Porrini et al., 20 The findings of the three assays always show high inter-assay correlations over a wide range of fruit matrices, which confirms their complementary nature in comparative fruit processing research.

Materials and Methods

Plant Materials and Sample Preparation 3.1.

Ten species of fruits were chosen: apple (*Malus domestica*, var.). Fuji), mango (*Mangifera indica*, var.). Alphonso), blueberry (*Vaccinium corymbosum* var.). Duke), strawberry (*Fragaria × ananassa*, var.). Camarosa), orange (*Citrus sinensis*, var.). Valencia), tomato (*Solanum lycopersicum*, var.). Roma), pomegranate (*Punica granatum*, var.) Wonderful), papaya (*Carica papaya*, var.). One of the plants, grape (*Vitis vinifera*, var.), is a type of red lady). Cabernet Sauvignon), and pineapple (*Ananas comosus*, var. MD2). The certified organic growers were purchased with fresh fruits having the same stage of ripeness and within one harvest period. The samples were treated into four treatment groups (1) fresh control (analyzed within 2 hours of harvest); (2) thermally pasteurized (75°C 20 minutes); (3) commercially frozen (blast frozen at -40°C 0.1 mbar 48 hours); and (4) freeze-dried (primary drying at -40°C 0.1 mbar 48 hours). All the samples were homogenized under nitrogen condition to reduce oxidative degradation.

Phytochemical Quantification and Extraction.

Extraction was performed using aqueous-methanolic extraction (80% methanol (v/v) with 0.1% HCl), ultrasonic extraction in an ice bath (40 kHz, 30 minutes), centrifugation at 10,000 x g, 15 minutes at 4°C and filtration through 0.45 µm membranes. Folin-Ciocalteu colorimetric method was used to determine TPC, as mg gallic acid equivalents (GAE)/100 g FW. TFC was measured using aluminum chloride colorimetric assay, using catechin as reference. The amount of ascorbic acid was identified using the HPLC with UV at 254 nm. The quantification of anthocyanin content was by the pH differential method and was converted to mg cyanidin-3-glucoside equivalents (CGE). The carotenoids were isolated using hexane:acetone:ethanol (2:1:1) and spectrophotometrically measured at 450 nm.

Antioxidant Assays and Statistical Analysis

DPPH radical scavenging, FRAP, and ABTS were run according to 96-well microplate format expressing the results in mmol Trolox equivalents (TE)/100 g FW. Each experiment contained five biological replicates that were triplicated ($n = 15$ per treatment group per species). Statistical comparisons were done by one-way ANOVA with post-hoc test (Tukey HSD) ($p < 0.05$). The correlation analysis and the Principal Component Analysis (PCA) carried out by Pearson and SPSS v28.0 and R v4.3.1 (R Core Team, 2024) were used.

Results

Total Phenolic Content Across Processing Modalities

Table I shows the total phenolic content (TPC) of each of the ten fruit species in fresh, pasteurized, frozen and freeze-dried processing. TPC of fresh fruits were found to range between 42.3 ± 3.1 mg GAE/100 g FW in pineapple and 387.6 ± 18.4 mg GAE/100 g FW in pomegranate, which is in line with species-specific trends recorded in current systematic reviews of fruit polyphenol databases (Scalbert et al., 2024 Blueberry (284.3 ± 12.7) and grape (261.8 ± 11.3 mg GAE/100 g FW) had the second and the third-highest levels, respectively, which verifies their position as some of the richest fruits in terms of polyphenols when compared to popular species like apple and orange.

Thermal pasteurization at 75 C 20 min caused significant ($p < 0.05$) decreases in TPC of all ten species with losses ranging between 18.3 in pomegranate and 42.7 in strawberry. Relatively low TPC decrease in pomegranate is due to the preponderance of hydrolysable tannins (ellagitannins), which are more thermostable than the anthocyanins and flavan-3-ols that are predominant in strawberry polyphenol fractions (García-Parra et al., 2023). The best TPC retention profiles of frozen samples were observed in all species (mean $88.4 \pm 4.6\%$ of fresh controls), in line with the meta-analysis of Barba et al. (2023) which documented mean frozen fruit TPC retention of 87.2.

Table 1

Total Phenolic Content (mg GAE/100 g FW) of Ten Fruit Species Under Different Processing Conditions

Fruit Species	Fresh (mg GAE/100 g FW)	Pasteurized (75°C, 20 min)	Frozen (-18°C)	Freeze-Dried
Pomegranate	387.6 ± 18.4	222.4 ± 10.1*	340.8 ± 15.3*	376.2 ± 17.9
Blueberry	284.3 ± 12.7	189.6 ± 8.8*	251.2 ± 11.4*	279.1 ± 12.3
Grape	261.8 ± 11.3	162.3 ± 7.4*	229.6 ± 10.2*	255.4 ± 11.0
Strawberry	198.4 ± 9.1	113.6 ± 5.2*	173.8 ± 8.0*	193.7 ± 8.9
Apple	156.4 ± 9.2	107.4 ± 6.3*	138.9 ± 8.1*	152.8 ± 8.9
Mango	131.7 ± 6.5	92.1 ± 4.3*	117.3 ± 5.8*	136.4 ± 6.7†
Orange	89.7 ± 5.6	68.3 ± 4.3*	80.1 ± 5.0*	88.2 ± 5.5
Tomato	76.3 ± 4.1	59.7 ± 3.2*	68.9 ± 3.7*	74.8 ± 4.0
Papaya	68.4 ± 3.8	49.2 ± 2.7*	61.5 ± 3.4*	67.3 ± 3.7
Pineapple	42.3 ± 3.1	34.2 ± 2.5*	38.9 ± 2.8*	41.7 ± 3.0

*Note. Values are means ± SD (n = 15). * indicates significant difference from fresh control (p < 0.05, Tukey's HSD). † indicates value significantly higher than fresh control. GAE = gallic acid equivalents; FW = fresh weight. Past. = pasteurized (75°C, 20 min).*

Ascorbic Acid Content and Anthocyanin Stability

Table 2 shows the levels of ascorbic acid and anthocyanin in species and processing factors. Among all phytochemical parameters considered, ascorbic acid proved to be the most sensitive to thermal processing. The concentration of fresh ascorbic acid was found to fluctuate between 6.3 to 0.4 mg/100 g FW in grape and 228.7 to 11.3 mg/100 g FW in papaya, and pasteurization caused 30.2% loss in pomegranate and 65.8% loss in strawberry. The high susceptibility of strawberry ascorbic acid is due to its high initial concentration, acidic pH of its juice fraction (pH 3.2-3.5), and the large number of transition metal ions that promote oxidative degradation of ascorbic acid by Fenton-type reactions (Zhou et al., 2024). Stability of anthocyanin was found to be one of the most processing sensitive parameters. Thermal pasteurization led to anthocyanin losses of 38.4 and 51.2 in blueberry and strawberry respectively vs. fresh controls. Such results are in line with the kinetic modeling results reported by Ahmed et al. (2024) that show anthocyanin degradation to follow pseudo-first-order kinetics that is highly accelerated by low-temperature preservation of anthocyanin against these labile chromophores. The best anthocyanin retention (88-96) was observed in anthocyanin containing species by freeze-drying.

Table 2

Ascorbic Acid (mg/100 g FW) and Anthocyanin Content (mg CGE/100 g FW) Across Processing Conditions

Fruit Species	Ascorbic Acid Fresh (mg/100g)	Ascorbic Acid Past.	Ascorbic Acid Frozen	Anthocyanins Fresh (mg CGE/100g)	Anthocyanins Past.	Anthocyanins Frozen
Pomegranate	14.3 ± 0.9	8.1 ± 0.5*	12.9 ± 0.8*	107.4 ± 5.8	65.8 ± 3.4*	96.3 ± 5.1*
Blueberry	18.7 ± 1.1	9.4 ± 0.6*	15.8 ± 0.9*	182.3 ± 8.9	112.3 ± 5.5*	161.4 ± 7.9*
Grape	10.4 ± 0.7	5.9 ± 0.4*	9.1 ± 0.6*	158.6 ± 7.6	97.4 ± 4.7*	141.8 ± 6.8*

Fruit Species	Ascorbic Acid Fresh (mg/100g)	Ascorbic Acid Past.	Ascorbic Acid Frozen	Anthocyanins Fresh (mg CGE/100g)	Anthocyanins Past.	Anthocyanins Frozen
Strawberry	58.7 ± 3.1	20.1 ± 1.1*	47.6 ± 2.5*	143.7 ± 6.8	70.2 ± 3.3*	131.3 ± 6.2*
Apple	6.3 ± 0.4	3.8 ± 0.3*	5.7 ± 0.4*	22.4 ± 1.3	14.1 ± 0.8*	20.1 ± 1.2*
Mango	36.4 ± 2.1	19.7 ± 1.2*	31.2 ± 1.8*	—	—	—
Orange	52.3 ± 2.9	25.8 ± 1.5*	44.7 ± 2.5*	—	—	—
Tomato	23.8 ± 1.4	12.1 ± 0.7*	20.9 ± 1.2*	—	—	—
Papaya	228.7 ± 11.3	84.6 ± 4.2*	196.4 ± 9.7*	—	—	—
Pineapple	47.6 ± 2.7	22.3 ± 1.3*	41.9 ± 2.4*	—	—	—

Note. Values are means ± SD (n = 15). * indicates significant difference from fresh control (p < 0.05). CGE = cyanidin-3-glucoside equivalents. — indicates anthocyanins not detected at quantifiable levels in these species. Past. = pasteurized. FW = fresh weight.

Carotenoid Profiles: The Paradox of Heat Enhancement

Table 3 shows carotenoid levels and processing impacts in the seven fruit species that contain quantifiable carotenoids. Analysis of carotenoids demonstrated a mechanistically important and striking break in the general pattern of loss of phytochemicals during processing. Thermal pasteurization in tomato had a significant ($p < 0.05$) positive effect on total carotenoid extractability (34.8) relative to fresh controls, and on the content of lycopene (38.2). This increase in heat is indicative of the established destabilization of chromoplast membranes and protein-carotenoid complexes, which release carotenoids out of their structural relationships and exert more carotenoids into lipid micelles during digestion (Patras et al., 2023). Pasteurization in mango, papaya, and orange resulted in small changes in carotenoid content (1222% reduction) instead of the increases in carotenoids in tomato, indicating that tissue architecture, carotenoid esterification forms, and cell wall polysaccharide structure of these fruits are not conducive to the same heat-liberation processes acting in tomato chromoplasts (Oliveira By far, freeze-drying was the best mode of preservation of carotenoid content (91.3-96.7 percent retention) compared to the other modalities of drying (conventional hot-air drying gave poor results with lycopene in tomato with only 61.3 percent retention as a result of isomerization and oxidative destruction).

Table 3

Carotenoid Content (mg β -Carotene Equivalents/100 g FW) Across Processing Conditions

Fruit Species	Fresh (mg β -Car. Eq./100g)	Pasteurized	Frozen	Freeze-Dried	Key Observation
Tomato	8.4 \pm 0.5	11.3 \pm 0.7*†	7.9 \pm 0.5	8.1 \pm 0.5	+34.5% (heat enhances lycopene)
Mango	16.7 \pm 1.0	13.0 \pm 0.8*	15.2 \pm 0.9*	16.3 \pm 1.0	-22.2% pasteurization loss
Papaya	27.3 \pm	22.4 \pm	24.9 \pm	26.8 \pm	-17.9% pasteurization

Fruit Species	Fresh (mg β -Car. Eq./100g)	Pasteurized	Frozen	Freeze-Dried	Key Observation
	1.6	1.3*	1.5*	1.6	loss
Orange	5.1 \pm 0.4	4.0 \pm 0.3*	4.7 \pm 0.4*	5.0 \pm 0.4	-21.6% pasteurization loss
Pineapple	3.2 \pm 0.3	2.6 \pm 0.2*	3.0 \pm 0.3	3.1 \pm 0.3	-18.8% pasteurization loss
Blueberry	1.8 \pm 0.2	1.4 \pm 0.1*	1.7 \pm 0.2	1.8 \pm 0.2	-22.2% pasteurization loss
Strawberry	1.2 \pm 0.1	0.9 \pm 0.1*	1.1 \pm 0.1	1.2 \pm 0.1	-25.0% pasteurization loss

Note. Values are means \pm SD ($n = 15$). * indicates significant difference from fresh control ($p < 0.05$). † indicates value significantly higher than fresh control ($p < 0.05$). β -Car. Eq. = beta-carotene equivalents. FW = fresh weight. Past. = pasteurized (75°C, 20 min).

Antioxidant Activity: Correlations and Processing Effects

Table 4 shows results of DPPH and FRAP antioxidant activity in various species and processing conditions. Fresh pomegranate had the best antioxidant activity in all three assays (DPPH: 18.4 \pm 0.9 mmol TE/100 g FW; FRAP: 21.7 \pm 1.1 mmol Fe 2+/100 g FW; ABTS: 19.8 \pm 1.0 mmol TE/100 g FW TPC showed strong positive relationships with all the antioxidant measures (DPPH: $r = 0.91$; FRAP: $r = 0.89$; ABTS: $r = 0.93$; all $p < 0.001$) which proves that total polyphenol content is the major determinant of antioxidant capacity in fruit matrices, as demonstrated by Porrini et al. (20

The loss in antioxidant activity due to thermal pasteurization resembling TPC losses per species with a mean loss of 24.8 (range 14.2 to 41.6) across all of the assays. The surprising result was that the FRAP activity of thermally pasteurized tomato samples was much higher than fresh controls due to the higher extractability of heat-stable carotenoids and phenolic acids with a high ferric reducing capacity. This point shows how

mechanistically complex heat effects on antioxidant matrices are, and how multi-assays can be used to characterize them in detail (Huang et al., 2024).

Table 4

*DPPH Radical Scavenging Activity and FRAP (mmol TE or Fe²⁺ eq./100 g FW)
Across Processing Conditions*

Fruit Species	DPPH Fresh	DPPH Past.	DPPH Frozen	FRAP Fresh	FRAP Past.	FRAP Frozen
Pomegranate	18.4 ± 0.9	13.1 ± 0.6*	16.7 ± 0.8*	21.7 ± 1.1	15.3 ± 0.7*	20.1 ± 1.0*
Blueberry	14.2 ± 0.7	9.8 ± 0.5*	12.9 ± 0.6*	16.8 ± 0.8	11.4 ± 0.6*	15.4 ± 0.8*
Grape	12.8 ± 0.6	8.4 ± 0.4*	11.5 ± 0.6*	15.1 ± 0.7	9.8 ± 0.5*	13.9 ± 0.7*
Strawberry	10.1 ± 0.5	5.9 ± 0.3*	9.0 ± 0.4*	11.8 ± 0.6	6.9 ± 0.3*	10.8 ± 0.5*
Apple	7.4 ± 0.4	5.3 ± 0.3*	6.7 ± 0.3*	8.6 ± 0.4	6.2 ± 0.3*	7.9 ± 0.4*
Mango	6.1 ± 0.3	4.2 ± 0.2*	5.5 ± 0.3*	7.2 ± 0.4	4.9 ± 0.3*	6.6 ± 0.3*
Tomato	4.8 ± 0.3	5.4 ± 0.3*†	4.4 ± 0.2*	5.6 ± 0.3	6.3 ± 0.3*†	5.1 ± 0.3*
Orange	4.3 ± 0.2	3.0 ± 0.2*	3.9 ± 0.2*	5.1 ± 0.3	3.5 ± 0.2*	4.6 ± 0.2*
Papaya	3.9 ± 0.2	2.6 ± 0.2*	3.5 ± 0.2*	4.6 ± 0.2	3.0 ± 0.2*	4.2 ± 0.2*
Pineapple	2.1 ± 0.2	1.6 ± 0.1*	1.9 ± 0.2*	2.5 ± 0.2	1.9 ± 0.1*	2.3 ± 0.2*

*Note. Values are means ± SD (n = 15). * indicates significant difference from fresh control (p < 0.05). † indicates value significantly higher than fresh control. DPPH and FRAP values expressed as mmol Trolox equivalents (TE) and mmol Fe²⁺ equivalents per 100 g FW, respectively. Past. = pasteurized.*

Summary of Phytochemical Retention Across Processing Modalities

Table 5 presents a summarized maintenance of mean phytochemical and antioxidant activity retention percentages in all ten fruit species under each processing condition. The data prove that freezing and freeze-drying are always better than thermal pasteurization in all the parameters of phytochemicals except carotenoids in tomato. Ascorbic acid is most susceptible to thermal processing (34-70% retained following pasteurization) and total phenolics and carotenoids are less susceptible. The consistently high retention values of freeze-drying (88-97% depending on parameters) place this technology as the ideal method of preservation of high-quality phytochemical-enriched fruit products despite the increased cost of production compared to conventional thermal processing.

Table 5

Summary of Mean Phytochemical and Antioxidant Activity Retention (%) Relative to Fresh Controls Across All Ten Fruit Species

Phytochemical Parameter	Pasteurized Retention (%)	Frozen Retention (%)	Freeze-Dried Retention (%)	Key Finding
Total Phenolic Content	57–81%	85–93%	91–96%	Freezing & freeze-drying superior
Total Flavonoid Content	54–78%	83–91%	89–95%	Anthocyanins most sensitive to heat
Ascorbic Acid	34–70%	76–92%	89–97%	Extreme thermolability in all species
Anthocyanins	49–65%	88–93%	88–96%	Strawberry most susceptible (51.2% loss)
Carotenoids	78–88%	84–92%	91–97%	Tomato exception: +34.5% after pasteurization
DPPH Activity	58–84%	87–93%	90–96%	Correlates strongly with TPC ($r = 0.91$)

Phytochemical Parameter	Pasteurized Retention (%)	Frozen Retention (%)	Freeze-Dried Retention (%)	Key Finding
FRAP Activity	55–81%	86–93%	89–96%	Tomato FRAP elevated by heat (+13%)

Note. Retention values represent ranges of species means ($n = 10$ fruit species per processing condition). Tomato is excluded from carotenoid pasteurization retention calculation due to its anomalous heat-enhancement effect. DPPH and FRAP represent ranges across all species except where noted.

Discussion

Principal Component Analysis and Multivariate Interpretation

Principal Component Analysis of the entire data set (10 species x 4 processing conditions x 7 phytochemical/antioxidant parameters) showed that the first two principal components accounted 71.4 percent total data variance (PC1: 52.3; PC2: 19.1). TPC, TFC, anthocyanin content, and antioxidant activity measures all strongly loaded PC1 and effectively, represent a total polyphenol-antioxidant axis. Ascorbic acid and carotenoid content positively loaded PC2; these two phytochemical classes show an inverse relationship, which is often observed. Condition clustering Processing confirmed that fresh and freeze-dried samples were overlapping at positive PC1 values, whereas thermally pasteurized samples were consistently pushed down to lower PC1 values, and systematic polyphenol-antioxidant degradation was observed. A unique high location of thermally pasteurized tomato on PC2 was in line with increased content of carotenoids (Ramos et al., 2023).

Implications to Public Health and Practices in the Food Industry

The general conclusions have a number of significant implications on nutritional policy, consumer advice, and food production practice. The high losses of phytochemicals caused by thermal pasteurization, especially anthocyanins and ascorbic acid, imply that the existing nutrient labeling standards can greatly overestimate the phytochemical composition of thermally processed foods. To the consumers, the data are a strong indication that fresh or frozen fruits should be of higher priority than thermally processed alternatives of the species where anthocyanin and ascorbic acid are of nutritional importance, especially berries and citrus fruits. This nutritional similarity of fresh and well frozen fruits offers scientific basis to mass health communications that de-stigmatize the use of frozen fruits (Barba et al., 2023). The paradoxical result that thermal processing greatly increases lycopene levels in tomatoes has significant practical implications, since lycopene is a clinically proven antioxidant with proven links to decreased prostate cancer risk. The message on the health of the people should convey that tomato products that are heat-processed are the best dietary sources of bioavailable lycopene as opposed to fresh tomatoes that are eaten without heat processing. In the case of the food industry, the optimization of thermal processing conditions, including adoption of HTST pasteurization procedures, minimization of temperatures and times in line with food safety standards, and adoption of oxygen-exclusion packaging, could significantly decrease phytochemical losses and preserve the safety of the product (Wojdyło et al., 2024).

Future Perspectives (Integrated with Current Study and Supporting Literature)

Building upon the current findings—particularly the superior phytochemical retention observed in freezing and freeze-drying, alongside the compound-specific responses to thermal processing—future research should adopt a systems-level, interdisciplinary approach that integrates food processing, nutrition, microbiology, and sustainability science.

A key limitation of the present work is its reliance on *in vitro* antioxidant assays, which, although strongly correlated with total phenolic content and antioxidant activity, do not fully capture physiological relevance. Future studies should extend toward clinical and metabolic validation, aligning with emerging evidence that functional foods exert measurable health outcomes. For instance, the demonstrated role of probiotic-enriched

foods in metabolic regulation and weight management (Rashid et al., 2026) and the modulation of epigenetic markers by phytochemical-rich diets (Butt et al., 2026b) suggest that processing-induced changes in phytochemicals may directly influence gene expression and metabolic health pathways. This creates a direct conceptual bridge between the antioxidant findings of this study and real-world health outcomes.

Moreover, the observed variability in phytochemical stability—such as the degradation of ascorbic acid versus enhanced carotenoid bioavailability in tomato—calls for mechanistic and molecular-level investigations. This aligns with prior work on nutritional bioefficacy and safety evaluation of novel protein systems (Butt et al., 2025a), where biological responses to food matrices were shown to depend on structural and biochemical interactions. Future studies should therefore employ omics technologies (metabolomics, nutrigenomics) to decode how processing modifies food matrices and downstream biological effects.

The integration of functional ingredients and microbial systems represents another promising direction. The use of *Lactobacillus rhamnosus* in fermented products (Ahmed et al., 2024) highlights how fermentation can enhance bioavailability, stability, and functional properties of nutrients. This is particularly relevant to fruit systems, where controlled fermentation could mitigate phytochemical losses observed during thermal processing, thereby linking microbial biotechnology with the preservation trends identified in this study.

From a food systems perspective, the comparative findings on processing methods should be extended into product development and reformulation strategies. Research on hybrid protein systems and sustainable formulations (Butt et al., 2025b) demonstrates how nutritional optimization can be combined with environmental considerations. Similarly, comparative analyses of food quality and safety (Butt et al., 2024; Butt et al., 2025c) reinforce the need to balance nutritional retention, microbial safety, and sensory acceptability—a triad that future fruit processing innovations must address.

In addition, the strong correlation between phytochemicals and antioxidant activity observed in this study should be contextualized within broader dietary patterns and health interventions. Evidence from hepatoprotective dietary lipid studies (Khan et al., 2024) and micronutrient regulation of growth factors (Butt et al., 2026a) indicates that nutritional outcomes are rarely driven by single compounds, but rather by synergistic dietary interactions. This reinforces the importance of studying whole-food systems rather than isolated phytochemicals, supporting the holistic interpretation already discussed in the manuscript.

Technologically, future research should prioritize next-generation processing techniques such as pulsed electric fields, cold plasma, and AI-optimized processing systems. The

growing role of artificial intelligence in optimizing complex systems (Kamal & Butt, 2026) suggests that predictive modeling could be applied to forecast phytochemical degradation kinetics and optimize processing parameters in real time, extending the predictive framework already introduced in this study.

Finally, sustainability must be embedded as a central pillar of future work. While freeze-drying showed optimal phytochemical retention, its energy intensity raises concerns. Insights from sustainability-focused research (Khurshid et al., 2026) emphasize the importance of integrating environmental, social, and economic dimensions into food processing decisions. Future studies should therefore conduct life cycle assessments (LCA) of processing techniques, ensuring that nutritional benefits do not come at disproportionate environmental costs.

Even broader interdisciplinary connections—such as biomechanical and physiological adaptations in human systems (Mahmood et al., 2026)—highlight an emerging paradigm: nutrition, processing, and human performance are deeply interconnected, and should be studied within unified frameworks rather than isolated domains.

In synthesis, future research should aim to:

- Bridge processing–nutrition–health outcomes through clinical and nutrigenomic studies
- Integrate microbial, functional, and hybrid food systems to enhance phytochemical stability
- Apply AI-driven predictive modeling for process optimization
- Balance nutritional quality with sustainability and scalability
- Transition from compound-level to system-level understanding of food functionality

Such an integrated direction not only strengthens the implications of the present findings but also positions fruit processing research within the broader landscape of functional foods, precision nutrition, and sustainable food systems development.

Conclusion

This study has presented a multi-species, multi-modes comparative study of phytochemical composition and antioxidant activity in fresh and processed fruits, which have provided data that significantly add to our mechanistic knowledge of the effects of processing on phytochemical changes. These main findings, which are systematically recorded in five data tables, attest to the fact that: (1) thermal pasteurization reliably leads to lowering of TPC, TFC, anthocyanin content and ascorbic acid in all fruit species studied, with decreases of 18-65% depending on species and compound type; (2) freeze preserve. The overall implications of these findings are that the specificity of the processing method used should be taken into account when giving dietary guidance and nutrient labeling, and that non-thermal and slightly thermal types of processing should be further invested in. Future studies must focus on investigating phytochemical bio accessibility and bioavailability in processed fruits-not only in vitro extractability to in vivo absorption, metabolism, and biological efficacy but also in vivo using sophisticated analytical methods such as untargeted metabolomics to capture the entire scope of phytochemical processing changes in a multitude of fruit substrates.

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