Quantification of Phytochemicals in Fresh and Dried Berries

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Abstract:

Phenolics, flavonoids, anthocyanins, and ascorbic acid are among the many health-promoting phytochemicals found in berries that support their anti-inflammatory, antioxidant, and medicinal qualities. However, these bioactive components can be drastically changed by post-harvest processing, especially drying. The effects of drying on the phytochemical content of eight fruit varieties—both commercially accessible and farm-sourced—from Surat, Gujarat, India, are evaluated both statistically and qualitatively in this study. Using spectrophotometric techniques, samples of blueberries, raspberries, mulberries, blackberries, gooseberries, star gooseberries, and Indian blackberries—both fresh and dried—were examined. The findings repeatedly showed that compared to their dried counterparts, fresh berries maintained noticeably larger amounts of ascorbic acid, flavonoids, anthocyanins, total phenolics, and carbs. Fresh blueberries and mulberries had the highest concentrations of phytochemicals among the samples. Significant decreases were caused by drying, especially in substances that were sensitive to heat and oxidation, like vitamin C and anthocyanins. These results demonstrate the superiority of fresh berries in providing health benefits and the significance of processing techniques in maintaining the nutritional and functionalintegrity of berries.

1. Introduction:

Berries are widely recognized for their nutritional richness and are cultivated extensively across regions such as Europe, North America, and Australia. These fruits are consumed in various forms—including fresh, frozen, and processed products like juices, jams, and dried snacks—due to their flavour, versatility, and health benefits. For instance, Australia's berry industry alone produced over 116,000 tonnes in 2018, with a market value exceeding $900 million, reflecting growing consumer demand (Hort Innovation, 2019).

Among the numerous berry varieties, species such as gooseberry, star gooseberry, Indian blackberry, and mulberry are of increasing scientific interest. These fruits are rich sources of phytochemicals, particularly polyphenolic compounds and vitamins, which contribute to their antioxidant and therapeutic potential. Research has consistently highlighted the role of these bioactive substances—including flavonoids, anthocyanins, phenolic acids, and ascorbic acid—in supporting human health by reducing oxidative stress and inflammation (Stoner et al., 2011; Skrovankova et al., 2015).

Phytochemicals, also referred to as secondary plant metabolites or dietary bioactives, are compounds characterized by aromatic rings and hydroxyl groups, enabling them to act as antioxidants and biological modulators (Williamson et al., 2017). The composition and concentration of these compounds vary across berry species and are significantly influenced

by processing methods such as drying. While drying improves shelf life and convenience, it can also degrade sensitive nutrients like vitamin C and certain polyphenols due to heat and oxidation (Lee & Kader, 2000).

Given the increasing consumption of dried berries and berry-based products, it is important to evaluate how drying impacts their phytochemical profile. This research focuses on the quantification and characterization of key phytochemicals—particularly ascorbic acid—in both fresh and dried forms of selected berries. The findings will contribute to a better understanding of how post-harvest processing affects nutritional quality and will inform strategies to preserve health-promoting compounds in berry products.

2. MATERIALS AND METHODS

Analytical-grade reagents were used for the extraction and analysis of bioactive compounds. Ethanol solutions (85% and 80%) used in the extraction procedures were procured from Finar Chemicals (Ahmedabad, India). Reagents for carbohydrate estimation, including Anthrone reagent, 2.5 N hydrochloric acid, and solid sodium carbonate, were also obtained from Finar. For total phenolic content analysis, Folin–Ciocalteu reagent, 20% sodium carbonate (Na_2CO_3), and catechol standard were supplied by Research Lab Fine Chem (Mumbai, India). The same supplier provided reagents for ascorbic acid determination, including 2,4-dinitrophenylhydrazine (DNPH), 4% oxalic acid solution, bromine water, and 80% sulfuric acid. Flavonoid quantification was performed using quercetin, methanol, 5% sodium nitrite ($NaNO_2$), 10% aluminum chloride ($AlCl_3$), and 1 M sodium hydroxide (NaOH), all purchased from Himedia (Mumbai, India). For anthocyanin analysis, ethanol, 0.1 M hydrochloric acid, 0.025 M potassium chloride, and 0.4 M sodium acetate were likewise sourced from Himedia.

2.1 Sample collection & Preparation

Fresh samples of blueberries, raspberries, mulberries, and blackberries were procured from a local supermarket in Surat, Gujarat, India. Additional samples, including gooseberries, star gooseberries, Indian blackberries and farm-grown mulberries, were collected directly from agricultural fields in the region. All specimens were taxonomically verified by experts in the Department of Biosciences at Veer Narmad South Gujarat University, where voucher specimens were archived for reference. Fruits were sorted according to ripeness, washed thoroughly with running tap water to remove surface contaminants, and weighed prior to storage. The cleaned samples were stored in sterilized glass containers at −18 °C until further processing for phytochemical analysis (Chaman et al., 2011; Jimenez-Garcia et al., 2018; Maurer et al., 2023).

Table 1: Common and Scientific Names of Various Berry Types Analysed.

Berry Type	Scientific Name	Common Name
Blueberry	Vaccinium corymbosum	Blueberry
Raspberry	Rubus idaeus	Raspberry
Mulberry (Black)	Morus nigra	Black Mulberry
Blackberry	Rubus fruticosus	Blackberry
Gooseberry	Phyllanthus emblica	Indian Gooseberry
Star Gooseberry	Phyllanthus acidus	Star Gooseberry
Indian Blackberry	Syzygium cumini	Indian Blackberry
Mulberry (Red)	Morus nigra	Red Mulberry

2.2 Extraction of Bioactive Compounds

Extraction for Dry Berries

Whole berry samples were thoroughly rinsed with running tap water to remove surface impurities, then sun-dried and homogenized into a fine paste. A 20 g portion of this paste was macerated in 200 ml of 85% ethanol and incubated at 37 °C for 24 hours with continuous agitation. After extraction, the mixture was filtered using Whatman No. 1 filter paper, and the filtrate was concentrated using a rotary evaporator to remove residual solvent. The resulting crude ethanol extract was stored and used for subsequent phytochemical analyses (Sadasivam and Manickam, 2008).

Extraction for Fresh Berries

Fresh berries were thoroughly rinsed under running water to eliminate any surface contaminants. A 1 g sample of each berry was ground with tenfold volume of 80% ethanol using a mortar and pestle to obtain a homogenate. This mixture was then centrifuged at 10,000 rpm for 20 minutes to separate the solid residue. The supernatant was collected, and the residue was subjected to a second extraction with fivefold volume of 80% ethanol. The supernatants from both extractions were combined and concentrated through evaporation to produce the final extract, which was subsequently used for phytochemical analysis (Sadasivam and Manickam, 2008).

2.3 Determination of Carbohydrate Content

Carbohydrate content was quantified using a modified Anthrone method (Sadasivam and Manickam, 2008). Initially, 100 mg of the sample was placed in a boiling tube and hydrolyzed by heating with 5 ml of 2.5 N HCl in a boiling water bath for three hours. The mixture was then cooled to room temperature and neutralized with solid sodium carbonate until effervescence ceased. The volume was adjusted to 100 ml with distilled water, and the solution was centrifuged. Aliquots of 0.5 ml and 1 ml of the supernatant were used for analysis. (Hewitt, 1958; Beck and Bibby, 1961).

For calibration, standard solutions were prepared using 0, 0.2, 0.4, 0.6, 0.8, and 1.0 ml of glucose working standard. Each standard and sample aliquot were made up to 1 ml with

distilled water, and 4 ml of Anthrone reagent was added to each tube. The mixture was then heated in a boiling water bath for eight minutes, rapidly cooled, and the green to dark green color was measured at 630 nm using a spectrophotometer. A standard curve was constructed by plotting the concentration of glucose standards (on the x-axis) against their respective absorbance values (on the y-axis). The carbohydrate content in the sample was determined by interpolating its absorbance on the standard curve.

2.4 Determination of Total Phenolic Content

The total phenolic content was assessed using the Folin-Ciocalteu method with some modifications (Sadasivam and Manickam, 2008). Dilutions of the berry extract were prepared with distilled water to achieve various volumes, ranging from 0.2 to 1 ml. Each aliquot was adjusted to a final volume of 3 ml with distilled water. Subsequently, 0.5 ml of Folin-Ciocalteu reagent was added to each test tube. After a reaction period of three minutes, 2 ml of 20% Na_2CO_3 solution was introduced. The mixture was thoroughly mixed and then heated in a boiling water bath for exactly one minute. Following heating, the tubes were allowed to cool to room temperature, and the absorbance was measured at 650 nm using a reagent blank for calibration.

The concentration of total phenolic content in the extracts was determined based on the standard calibration curve of catechol. The phenolic content was expressed in µg/ml, and the concentration was calculated using the following formula:

$$\text{Concentration } (\mu g/ml) = \frac{\text{Absorbance at 650 nm}}{\text{Slope of the Calibration Curve}}$$

2.5 Determination of Flavonoid Content

The total flavonoid content was quantified using the aluminum chloride colorimetric assay, as described by Phuyal et al. (2020). A stock solution of quercetin (4 mg/mL) was prepared methanol. This stock solution was serially diluted to obtain final concentrations of 0.25 mg/mL, 0.5 mg/mL, 0.75 mg/mL, and 1 mg/mL. Aliquots of 1 ml of each quercetin solution were combined with 4 ml of distilled water in test tubes. To each test tube, 0.3 ml of 5% $NaNO_2$ solution was added, followed by 0.3 ml of 10% $AlCl_3$ solution after 5 minutes. After an additional 6 minutes, 2 ml of 1 M NaOH was added to the mixture. The total volume was adjusted to 10 ml with 4.4 ml of distilled water, and the optical density (OD) was measured at 510 nm. The total flavonoid content was expressed as quercetin equivalents, calculated from the linear regression equation derived from the calibration curve.

2.6 Determination of Anthocyanin Content

The anthocyanin content in the berry extracts was quantified using the pH differential method. For extraction, the berries were first processed into a puree. The extraction solvent

was prepared by mixing ethanol with 0.1 M hydrochloric acid in a ratio of 85:15 (v). A 1:2 (w) ratio of fruit puree to extraction solvent was employed. The mixture was stirred continuously using a magnetic stirrer for 1 hour to ensure thorough extraction. Following extraction, the solution was filtered, and the resulting filtrate was used for analysis.

To determine the anthocyanin content, aliquots of the filtered extract were diluted with buffer solutions to measure absorbance at different pH levels. Two buffer solutions were prepared: pH 1 buffer and pH 4.5 buffer. (Ivanovic et al., 2014)

For each sample, a series of dilutions were prepared by mixing one part of the berry extract with four parts of the respective buffer to prevent exceeding the buffer capacity. The absorbance of the samples was measured at wavelengths of 520 nm and 700 nm using distilled water as blank.

The anthocyanin content was calculated using the formula:

$$\text{Anthocyanin pigment (mg/L)} = \frac{A \times \text{MW} \times \text{DF} \times V \times 1000}{a \times l \times m}$$

Where the absorbance (A) was measured at 520 nm; the molecular weight (MW) of cyanidin-3-glucoside, which is 449.2 g/mol; and the molar absorptivity (a) of cyanidin-3-glucoside, which is 26,900 L/mol/cm. The calculation also considered the dilution factor (DF), the volume (V) of the extract used in milliliters, the path length (l) of the cuvette set at 1 cm, and the mass (m) of the sample in grams. These values were applied to determine the total monomeric anthocyanin content, expressing the result as milligrams of cyanidin-3-glucoside equivalents per gram of sample.

2.7 Determination of Ascorbic Acid Content

Ascorbic acid (Vitamin C) content was determined using a colorimetric assay involving 2,4-dinitrophenylhydrazine (DNPH), as described by Sadasivam and Manickam (2008). For extraction, 5 grams of the sample were ground with a pestle and mortar in 50 mL of 4% oxalic acid solution. The mixture was centrifuged, and the supernatant was collected. An aliquot of 10 mL from this supernatant was placed into a conical flask, and bromine water was added dropwise with constant stirring until the solution turned orange-yellow, indicating excess bromine. The excess bromine was expelled by blowing air into the solution, and the volume was adjusted to 50 mL with 4% oxalic acid solution.

For analysis, 3 mL of the brominated extract was diluted with distilled water, followed by the addition of 1 mL of 2% DNPH reagent and one or two drops of thiourea. The mixture was incubated at 37°C for three hours. After incubation, 7 mL of 80% sulfuric acid was added to dissolve the resulting orange-red osazone crystals. The absorbance was measured at 540 nm using a spectrophotometer. The concentration of ascorbic acid was determined by comparing

the absorbance to a standard calibration curve. (Bajaj and Kaur, 1981; Hewitt and Dickes, 1961)

3. RESULTS AND DISCUSSION

Comparative Analysis of Bioactive Compounds in Fresh and Dry Berries

Table 2: Phytochemical Content (Carbohydrate, Phenol, Flavonoid, Anthocyanin, and Ascorbic Acid) in Fresh and Dried Berries.

Berries		Carbohydrate (mg/ml)	Phenol (µg/ml)	Flavonoid (mg/ml)	Anthocyanin (mg/100g)	Ascorbic acid (mg/ml)
Blackberry (Frozen)	Fresh	59.2 ±0.35	468.8±0.45	2.63±0.29	135.4±0.52	1.07±0.39
	Dry	33.5±0.82	415.3 ±0.51	2.05±0.37	98.65±0.22	0.35±0.38
Blueberry (Frozen)	Fresh	67.5±0.41	514.35 ±0.18	2.79±0.42	266.01± 0.36	1.87±0.19
	Dry	27.3±0.46	420.1 ±0.52	2.66±0.35	198.54±0.36	0.62±0.32
Raspberry (Frozen)	Fresh	66.17±0.64	342.34 ±0.32	3.03±0.53	138.02±0.31	2.43±0.27
	Dry	30.50±0.47	302.4 ±0.43	1.59±0.48	124.32±0.45	0.91±0.36
Mulberry (Frozen)	Fresh	70.05±0.21	352.9 ±0.71	3.55±0.84	226.06±0.47	2.38±0.47
	Dry	42.83±0.31	295.6 ±0.57	1.99±0.29	187.52±0.32	0.79±0.24
Gooseberry (Farm)	Fresh	05.04±0.37	354.8±0.13	1.34±0.82	3.5±0.41	4.45±0.45
	Dry	02.03±0.31	160.5±0.61	0.31±0.21	1.45±0.51	1.75±0.64
Star Gooseberry (Farm)	Fresh	12.06±0.74	234.6±0.35	0.45±0.23	2.8±0.23	3.41±0.24
	Dry	07.31±0.51	97.21±0.74	0.11±0.15	0.34±0.56	1.32±0.34
Indian Blackberry (Farm)	Fresh	10.02±0.35	341.5±0.51	2.65±0.24	168.5±0.34	2.46±0.27
	Dry	06.05±0.45	151.7±0.13	1.02±0.41	78.03±0.34	0.32±0.86
Mulberry (Farm)	Fresh	55.54±0.72	375.9±0.42	3.73±0.25	126.7±0.21	2.12±0.15
	Dry	31.36±0.32	178.45±.14	1.71±0.64	75.23±0.76	0.64±0.56

3.1 Carbohydrate content

Fresh mulberry had the highest carbohydrate level (70.05 mg/ml), while dried blueberry had the lowest (27.3 mg/ml). Among the samples, dried mulberries demonstrated the highest carbohydrate retention, suggesting superior sugar stability during drying. Notable reductions were observed in gooseberry (from 5.04 ± 0.37 to 2.03 ± 0.31 mg/ml), star gooseberry (12.06 ± 0.74 to 7.31 ± 0.51 mg/ml), Indian blackberry (10.02 ± 0.35 to 6.05 ± 0.45 mg/ml), and mulberry (55.54 ± 0.72 to 31.36 ± 0.32 mg/ml). The carbohydrate content decreased significantly in all berries after drying, primarily due to the leaching of water-soluble sugars and thermal degradation of polysaccharides. These findings align with previous studies reporting that drying processes can lead to sugar loss through heat-induced mechanisms such as the Maillard reaction and caramelization (Huang et al., 2019; Nsombo et al., 2017; Ahmed et al., 2013; Vega-Gálvez et al., 2009).

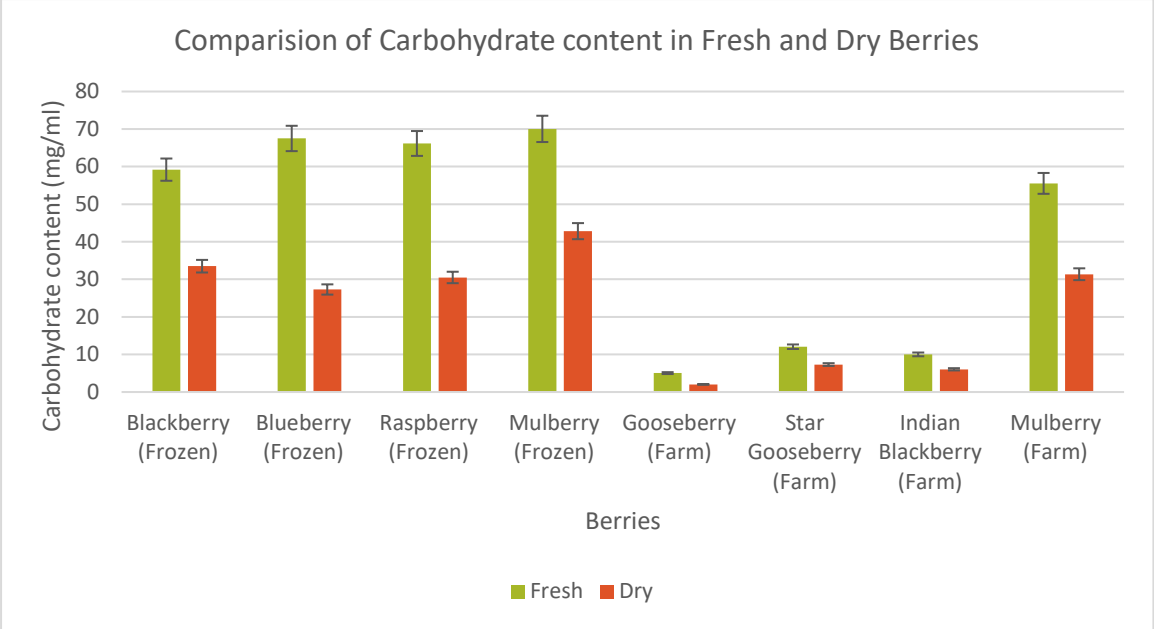

Figure 1: Carbohydrate Content in Fresh and Dry Berries

3.2 Phenol content

Phenolic content was higher in all fresh (frozen) berry samples compared to their dry forms. Blackberry decreased from 468.8 ± 0.45 to 415.3 ± 0.51 µg/ml, and blueberry dropped from 514.35 ± 0.18 to 420.1 ± 0.52 µg/ml. Raspberry and mulberry also exhibited reductions from 342.34 ± 0.32 to 302.4 ± 0.43 µg/ml, and 352.9 ± 0.71 to 295.6 ± 0.57 µg/ml, respectively.

Phenol content was significantly higher in the fresh form of all farm berries compared to their dry counterparts. Gooseberry dropped from 354.8 ± 0.13 to 160.5 ± 0.61 µg/ml, star gooseberry from 234.6 ± 0.35 to 97.21 ± 0.74 µg/ml, Indian blackberry from 341.5 ± 0.51 to 151.7 ± 0.13 µg/ml, and mulberry from 375.9 ± 0.42 to 178.45 ± 0.14 µg/ml.

The notable reduction in phenolic content following drying can be attributed to the thermal sensitivity of polyphenolic compounds. Elevated temperatures and extended exposure to oxygen during the drying process promote oxidation and degradation of these bioactive constituents. This decline is further compounded by enzymatic oxidation and the leaching of water-soluble phenolics. Similar trends have been reported in previous research, which documented substantial losses of phenolic compounds as a result of thermal processing and dehydration (Pinela et al., 2011; Nicoli et al., 1999).

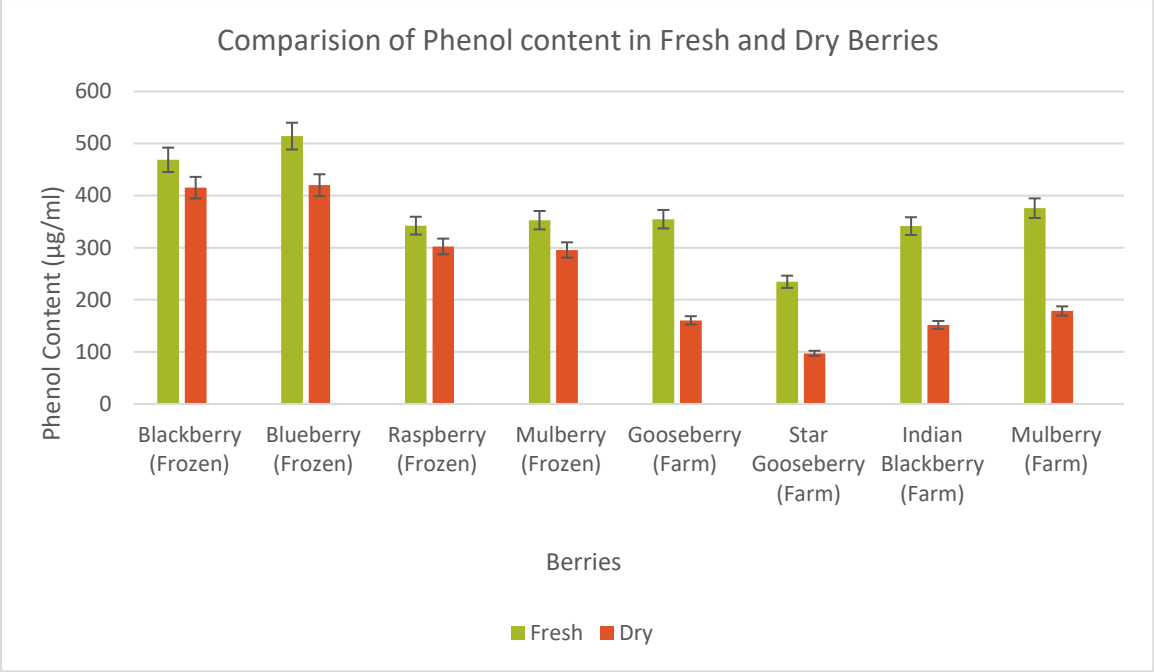

Figure 2: Phenol Content in Fresh and Dry Berries

3.3 Flavonoid content

The flavonoid content was higher in the fresh (frozen) forms of all berries compared to their dry counterparts. Blackberry showed a decrease from 2.63 ± 0.29 to 2.05 ± 0.37 mg/ml, and blueberry had a slight reduction from 2.79 ± 0.42 to 2.66 ± 0.35 mg/ml. Raspberry and mulberry exhibited more pronounced losses, with raspberry dropping from 3.03 ± 0.53 to 1.59 ± 0.48 mg/ml and mulberry from 3.55 ± 0.84 to 1.99 ± 0.29 mg/ml.

Flavonoid content was significantly higher in fresh farm berries compared to their dry forms. Gooseberry decreased from 1.34 ± 0.82 to 0.31 ± 0.21 mg/ml, and star gooseberry showed a drastic reduction from 0.45 ± 0.23 to 0.01 ± 0.15 mg/ml. Indian blackberry dropped from 2.65 ± 0.24 to 1.02 ± 0.41 mg/ml, while mulberry had the highest content, reducing from 3.73 ± 0.25 to 1.71 ± 0.64 mg/ml.

The observed reduction in flavonoid levels post-drying can be primarily attributed to thermal degradation and oxidative processes. Flavonoids are known for their sensitivity to heat and environmental conditions during processing, making them vulnerable to breakdown under high drying temperatures. This decline is consistent with findings from earlier studies that reported substantial flavonoid loss due to the heat sensitivity of these compounds during dehydration (Patras et al., 2010; Skrede et al., 2000; Wojdyło et al., 2009).

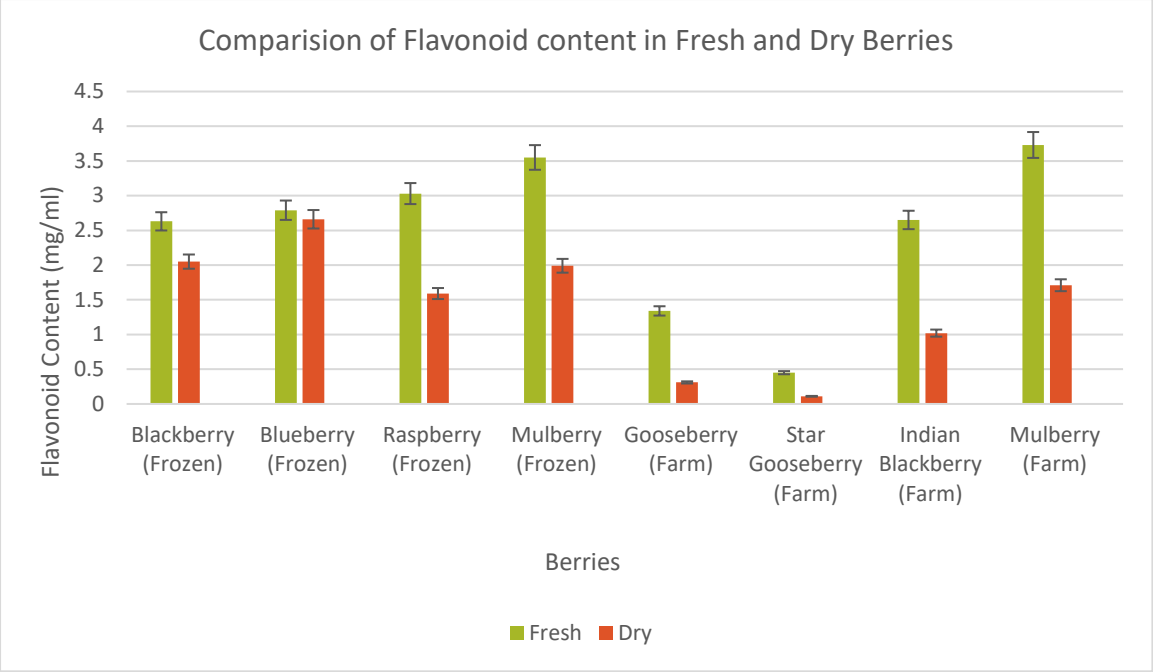

Figure 3: Flavonoid Content in Fresh and Dry Berries

3.4 Anthocyanin content

Anthocyanin content was consistently higher in the fresh (frozen) berries compared to their dry counterparts. In blackberry, levels dropped from 135.4 ± 0.52 to 98.65 ± 0.22 mg/100g, while blueberry showed a marked decline from 266.0 ± 0.36 to 198.54 ± 0.36 mg/100g. Similarly, raspberry decreased from 138.02 ± 0.31 to 124.32 ± 0.45 mg/100g, and mulberry from 226.06 ± 0.47 to 187.52 ± 0.32 mg/100g.

Anthocyanin content was notably higher in all fresh farm berries than in their dry forms. Gooseberry dropped from 2.5 ± 0.41 to 0.45 ± 0.51 mg/100g, and star gooseberry from 2.8 ± 0.23 to 0.34 ± 0.56 mg/100g. Indian blackberry showed a substantial decline from 168.5 ± 0.34 to 78.03 ± 0.34 mg/100g, and mulberry from 126.7 ± 0.21 to 75.23 ± 0.76 mg/100g.

The marked reduction in anthocyanin content following the drying process can be attributed to the compound's inherent sensitivity to heat, oxygen, and pH fluctuations. These factors contribute to the oxidative degradation and structural breakdown of anthocyanin molecules during thermal processing. The thermal instability of anthocyanins has been widely recognized, with previous studies confirming their susceptibility to degradation under drying conditions (Sadilova et al., 2006; Capanoglu et al., 2008).

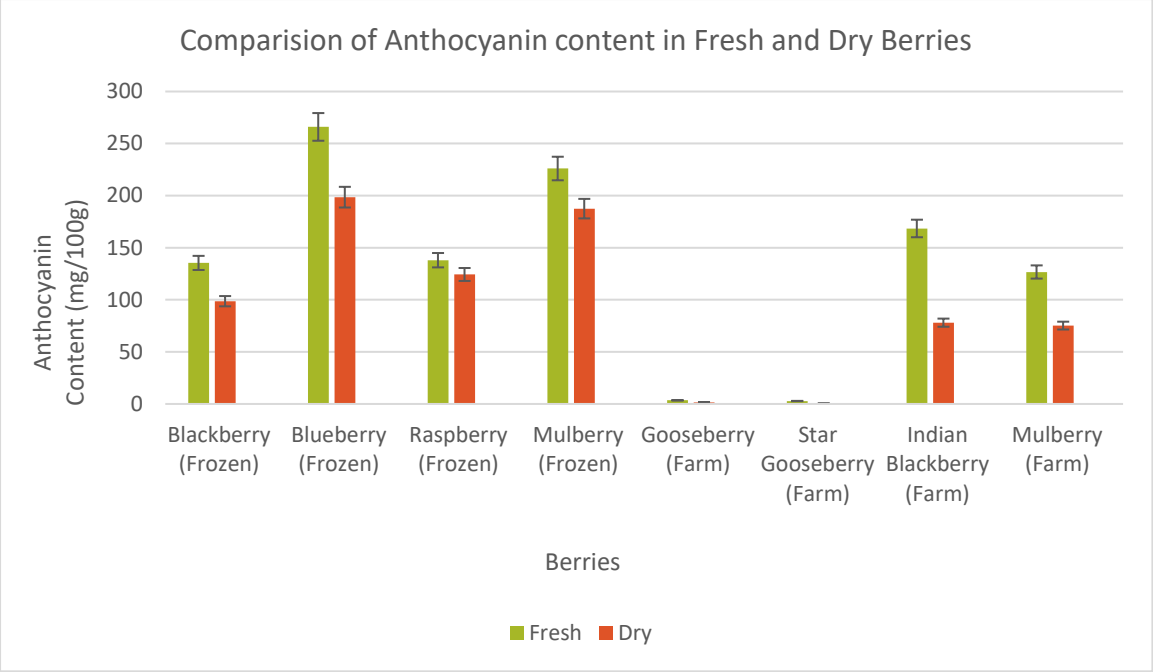

Figure 4: Anthocyanin Content in Fresh and Dry Berries

3.5 Ascorbic acid content

The ascorbic acid content was significantly higher in all fresh (frozen) berries compared to their dry forms. In blackberry, vitamin C dropped from 1.07 ± 0.39 to 0.35 ± 0.38 mg/ml. Blueberry showed a sharp decline from 1.87 ± 0.19 to 0.62 ± 0.32 mg/ml. Raspberry and mulberry also exhibited notable reductions—from 2.43 ± 0.27 to 0.91 ± 0.36 mg/ml, and 2.38 ± 0.47 to 0.79 ± 0.24 mg/ml, respectively.

Among the fresh samples, Gooseberry (Farm) showed the highest concentration (4.45 ± 0.45 mg/ml), while Mulberry (Farm) recorded the lowest (2.12 ± 0.15 mg/ml). Drying resulted in a considerable reduction in vitamin C across all berry types, with the most pronounced decrease observed in Indian Blackberry, where levels dropped from 2.46 to 0.32 mg/ml. This substantial loss is likely due to thermal and oxidative degradation during processing, consistent with previous findings that highlight vitamin C's vulnerability to processing and storage conditions (Lee & Kader, 2000; Rickman et al., 2007; Iqbal et al., 2004).

The reduction in ascorbic acid observed across all dried berry samples can be attributed to the compound's high sensitivity to heat, oxygen, and light during the drying process. Ascorbic acid (vitamin C) is widely recognized as one of the most heat-labile nutrients, and its rapid degradation during thermal processing and subsequent storage has been well-documented (Lee & Kader, 2000; Rickman et al., 2007).

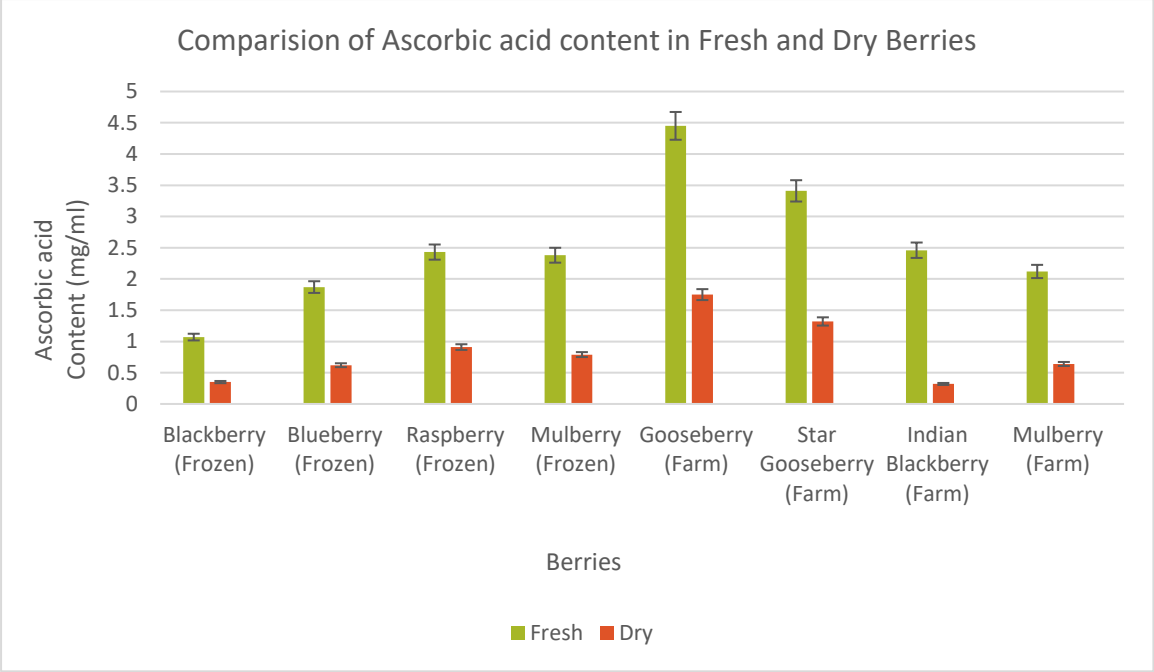

Figure 5: Ascorbic acid Content in Fresh and Dry Berries

3.6 Phytochemical analysis of berries-statistical visualization

PCA Analysis of Fresh Berries Based on Phytochemical Content

Principal Component Analysis (PCA) was employed to visualize the grouping patterns of different berry types based on their phytochemical profiles. The PCA biplot revealed clear separation and clustering among the berry varieties, highlighting differences and similarities in their bioactive compound content. Notably, blueberry and mulberry (farm) are positioned at opposite ends of the PCA1 axis, reflecting their high anthocyanin and flavonoid content, respectively. Gooseberry and star gooseberry formed a distinct cluster, largely influenced by their exceptionally high ascorbic acid content but lower levels of other phytochemicals. In contrast, blackberry, raspberry, and Indian blackberry appeared more centrally located, suggesting moderate and well-distributed phytochemical levels across all five parameters. These clustering patterns indicate that PCA can effectively distinguish berry types based on their nutritional signatures, offering insights for selecting specific berries for targeted health benefits or industrial use.

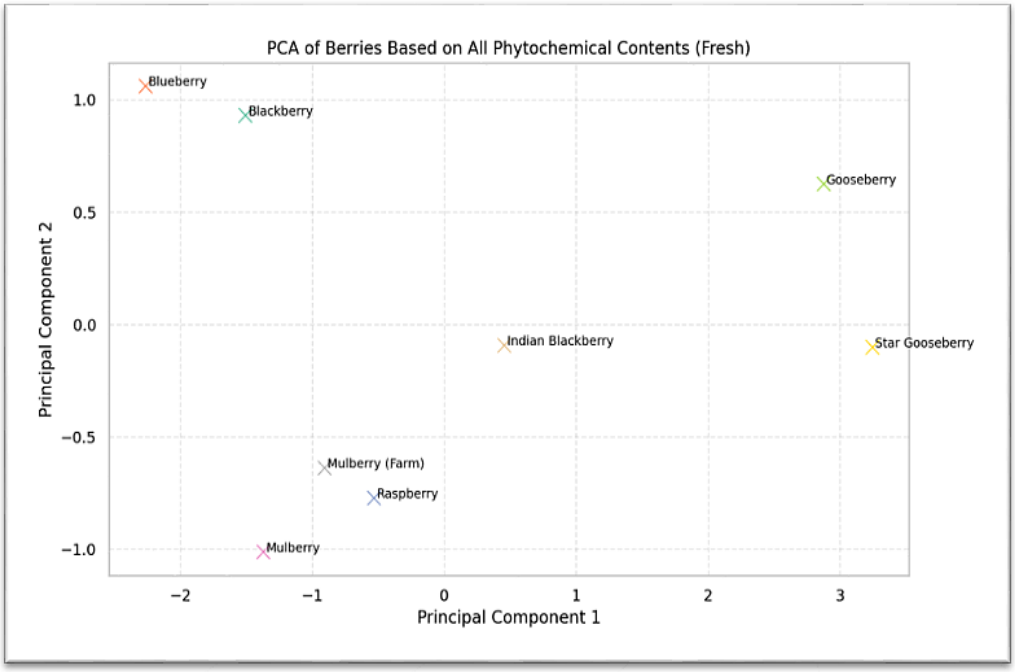

Figure 6: Principal Component Analysis of Fresh Berries

PCA Analysis of Dry Berries Based on Phytochemical Content

Principal Component Analysis (PCA) was applied to phytochemical data from dried berry samples to evaluate their clustering behaviour. The PCA plot illustrates clear grouping patterns, indicating significant differences in phytochemical retention post-drying. Blueberry and mulberry (farm) again positioned at distant extremes on the PCA1 axis, suggesting that they retain relatively high anthocyanin and flavonoid content even after drying. Conversely, star gooseberry and gooseberry clustered closely, characterized by diminished levels of most phytochemicals despite initially high vitamin C. Blackberry and raspberry occupied an intermediate position, showing moderate retention across parameters. These patterns suggest that while drying universally reduces phytochemical levels, its impact varies among berry types, with certain berries like blueberry preserving more functional properties than others.

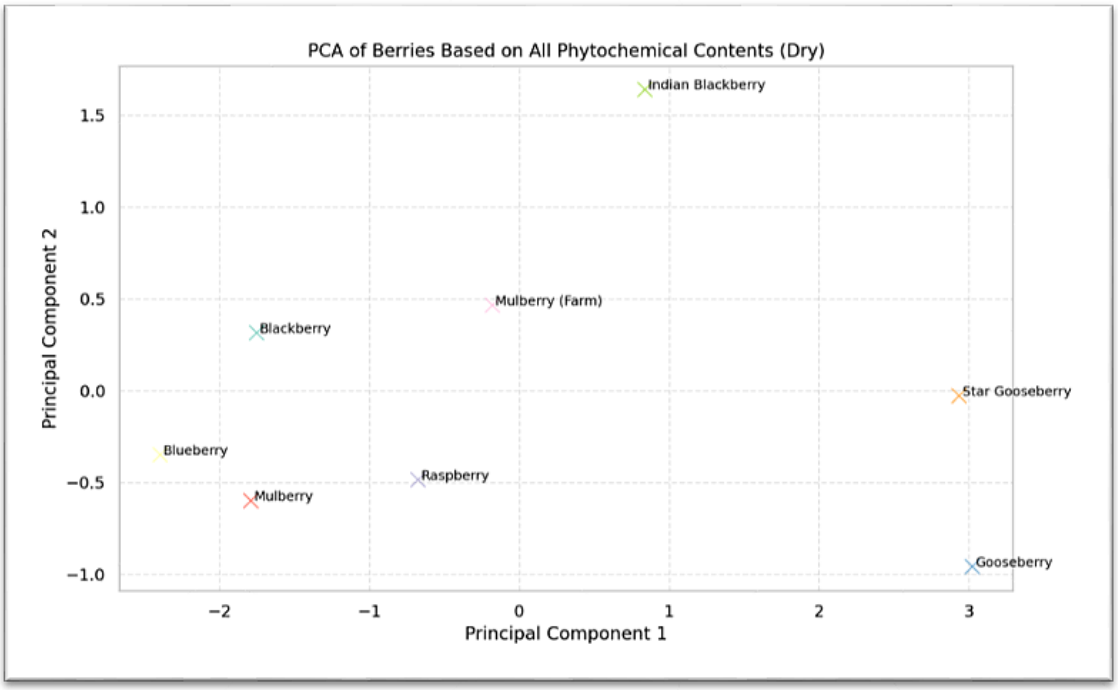

Figure 7: Principal Component Analysis of Dry Berries

4. CONCLUSION

According to this study, fresh berries always have larger concentrations of phytochemicals, such as ascorbic acid, flavonoids, phenolics, carbohydrates, and anthocyanins, than their dried counterparts. Although drying increased shelf life and made storage easier, it also resulted in a large loss of components that are susceptible to heat and oxidation, especially vitamin C and anthocyanins. Gooseberries were particularly high in ascorbic acid, whereas blueberries and mulberries had the highest quantities of bioactive chemicals in their fresh form among the fruits that were evaluated. The losses that were seen during the drying process emphasise how crucial it is to maximise post-harvest processing in order to maintain nutritional quality. Overall, the results highlight the need for better drying techniques to reduce nutrient degradation and support the higher health-promoting potential of fresh berries, guaranteeing that customers may take advantage of the functional qualities of berries in both their fresh and processed forms.

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