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Application of dielectric barrier discharge cold plasma for improving quality and shelf life of cantaloupe–sugarcane-blended juice

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Abstract

Sugarcane provides natural sweetness and possible health advantages, while cantaloupe, a fruit rich in nutrients, offers vitamins A and C, potassium, and antioxidants. These components add up together to provide a nourishing and revitalizing drink. The impact of dielectric barrier discharge cold plasma (DBDCP) on the quality of cantaloupe–sugarcane-blended juice was examined using an experimental design for varied processing duration (5–15 min), and helium and argon gas flow rate (10 mL/min). DBDCP produces cold plasma (CP), a nonthermal technique that alters food characteristics without causing heat harm. Physicochemical characteristics and bioactive substances were assessed before and after processing. Physicochemical analyses revealed changes in color, pH, and total soluble solids. When CP treatment was applied, it was observed that pH, Brix, and acidity changed from 5.20–5.39, 12.3–12.4, and 0.3–0.40%, respectively. Assessments of phytochemicals revealed variations in total phenolics (131.6–152.27 mg gallic acid equivalent [GAE]/100 mL), total flavonoid content (51.20–56.54 mg catechin equivalent [CE]/100 mL), total flavanol content (12.20–11.57 mg quercetin equivalent [QE]/100 mL), and antioxidant activity (74.3–88.1 mg ascorbic acid equivalent [AAE]/mL). The juice's safety improved as microbiological investigation showed a decrease in total plate count (2.70–1.65 log colony-forming unit [CFU]/mL) and mold count (2.31–1.41 log CFU/mL). Potential enhancements in taste and general appeal were discovered through the evaluation of sensory qualities. The findings imply that DBDCP treatment may be a useful technique for enhancing the safety and quality of blended juice prepared from sugarcane and cantaloupe. With its potential to improve the nutritional, microbiological, and sensory qualities of fruit juices, this study adds to the expanding body of research on the uses of CP technology in food processing.

Keywords: antioxidants; innovative nonthermal technology; juices preservation; phytochemicals; shelf life

Introduction

Sugarcane juice, because of its substantial health advantages, is a significant natural health beverage in subtropical and tropical nations. In the health-oriented consumer market, sugarcane juice competes with other soft beverages, resulting in economic advantages for sugarcane growers (Kaavya *et al.*, 2019). Sugarcane (*Saccharum officinarum* L.), a member of the Poaceae family, is a prominent industrial crop of considerable global economic significance. It functions as a principal cash crop and supplies raw materials for sugar and associated goods (Bridhikitti *et al.* 2023). It is ranked among the 10 most cultivated crops globally and is extensively dispersed in tropical and subtropical climates (Dhansu *et al.*, 2023). In addition to its invigorating flavor, sugarcane juice is rich in essential nutrients, such as organic acids, sucrose, natural sugars, and a plethora of minerals, such as zinc, sodium, potassium, iron, calcium, and magnesium (Dhansu *et al.* 2023; Hussain *et al.*, 2024a). Furthermore, it includes substantial proteins, soluble fiber, phytonutrients, such as chlorophyll, antioxidants, and vitamins A, C, and B complex (B1, B2, B3, B5, and B6), in addition to various other health-promoting substances (Chen *et al.* 2024).

Cantaloupe (*Cucumis melo* L.) is one of the most popular fruits consumed globally because of its flavor and health advantages (Shi *et al.,* 2025; Fatima *et al.*, 2023). Cantaloupe, a member of the Cucurbitaceae family, encompasses a number of crops having significant global economic importance. It is widely used in both cooking and medicines. Cantaloupe, which is mostly grown and eaten in Europe, is one of the several economically significant species in the Cucurbitaceae family (Vella *et al.*, 2019). The origin of melons has been debated for a long and remains a mystery (Adıgüzel *et al.*, 2023). In 2020, 28.5 million tons of melons were produced globally. Globally, China leads in melon production with 13.8 million tons, followed by Turkey with 1.7 million tons (Adıgüzel *et al.*, 2023).

Nonthermal methods, such as gamma irradiation, ultraviolet light, pulsed electric fields, ozone, plasma, and high hydrostatic pressure, have been investigated for food processing (Pasquali *et al.* 2016). Cold plasma (CP) is ionized gas with highly excited atomic, molecular, ionic, and radical entities, containing numerous reactive species such as electrons, positive and negative ions, free radicals, gas atoms, and quanta of electromagnetic and ultraviolet radiation (Paixão *et al.*, 2019). CP is a contemporary technical advancement designed to enhance and maintain the quality and safety of food items. CP treatment possesses strong antibacterial capabilities, reduces processing time, and functions at lower temperatures (often 30–50°C), thus maintaining nutritional and sensory attributes of food items (Kumar *et al.*, 2024). Because no prior research is conducted for creating cantaloupe and sugarcane mix juice, a combination of these two was used to create a unique beverage that combines the nutritional benefits of both. The juice's safety and purity could be compromised by enzymatic browning, oxidation, and microbiological growth induced by the blending process. Historically, fruit juices have been preserved using heating techniques. However, these techniques could destroy nutrients, bioactive substances, and sensory elements by excessive heat, thus lowering the juice's overall quality. On the other hand, CP offers a nonthermal preservation technique that improves the juice's stability, deactivate enzymes, and reduce microbial load while maintaining its nutritional value and flavor. The aim of this study was to assess the impact of dielectric barrier discharge cold plasma (DBDCP) operating settings (helium [He] and argon [Ar] gas flow and treatment duration) on pH, Brix, acidity, vitamin C, antioxidant activity, total phenolic contents (TPC), total flavonoid contents (TFC), total flavanol contents, and microbial load in cantaloupe–sugarcane-blended juice. To the best of our knowledge, no prior research exists on the preparation of nonthermal-treated blended juice from cantaloupe and sugarcane. Thus, this study was carried out with the objectives to assess the effect of DBDCP on the physicochemical and phytochemical characteristics of blended juice, to evaluate the treated juice's sensory acceptability and microbiological safety, and to ascertain the ideal DBDCP treatment parameters.

Material and Methods

Purchasing of raw materials

All reagents and chemicals used in the current research were acquired from Fluka Chemical Co. (Buchs, Switzerland) and Merck (Darmstadt, Germany). High-quality, fresh, and fully matured cantaloupes were acquired from the local market of Sargodha, Pakistan. Fresh sugarcanes of the CoL54 variety were procured from the local market of Sargodha, Pakistan. All the chemicals and reagents used in this study were of the same grade to avoid fluctuations in results. Each analysis was performed in triplicate and results were acquired as mean values and standard deviation (SD).

Pretreatment of fruits

Cantaloupe fruit was thoroughly washed with tap water and disinfected to eliminate dirt, dust, and other extraneous impurities. Its seeds were separated manually from the fruit. Sugarcane was separated from accompanying green plant parts and extraneous elements, and thoroughly cleansed for juice extraction.

Extraction and blending of juice

Cantaloupe and sugarcane juices were separately extracted by utilizing a blender (model No. NB-4020 Panasonic Industry, Berhad, Malaysia) and a conventional crusher (SXZ-300, China), respectively. Both juices were filtered through a screen with a pore size of 0.8 mm to exclude any extraneous impurities present in the juice. The Brix (measured in degrees Brix [°B]) of the blended juice was measured by using a hand refractometer (3840-PAL, alpha, Atago, Japan). The Brix of the blended juice was adjusted up to 12° by mixing 70 mL of cantaloupe juice and 30 mL of sugarcane juice. The research was carried out at the Institute of Food Science and Nutrition, University of Sargodha, Pakistan. Both juices were stored in an aseptic environment and subjected to further nonthermal treatments. The processed juices were intermittently employed for diverse analyses while stored in a refrigerator at 4°C. The entire protocols of juice preparation and storage were derived from the methods outlined by Khandpur and Gogate (2015), with necessary adjustments. The treatment strategy for the preparation of blended juice prior to analysis is outlined in Table 1.

Cold plasma treatment

Cold plasma treatment was afforded to the blended juice by following the methodology described by Manzoor *et al.* (2020), with slight amendments. A sample of sugarcane and cantaloupe-blended juice was placed in a 60-mm petri dish and subsequently placed into a dielectric barrier discharge (DBD) reactor. This apparatus has two electrodes (outer diameter of 50 mm) and a plexiglass dielectric barrier with a thickness of 1.2 mm. The apparatus has a transformer (CTP-2000; Corona Lab, Nanjing; Susan Plasma Tech., Co. Ltd., China) that was utilized for the applied voltage. Two types of gases He and Ar were used for plasma generation. The transformer received an input power of 0–220 V at a frequency of 10 Hz from the primary source. The samples were treated at a temperature of 30±2°C and a voltage of 70 V for 90 s, with a gas flow rate of 10 mL/min. All samples were chilled in an ice-water bath and maintained at 4°C until subsequent analysis.

Table 1. Treatment plan for cantaloupe–sugarcane-blended juice.

Treatments	Preservation technique	Specifications
CSJ0	Negative control	-
CSJ+	Positive control	Preservatives @ 1 g/L
T1	Cold plasma	Carrier gas: He
T2	Cold plasma	Carrier gas: Ar

Notes. CSJ+: positive control; CSJ0: negative control; T1: He-treated sample; T2: Ar-treated sample.

Storage of juice

Untreated and CP-treated juices were stored in sterilized bottles at 4°C for 4 months post-processing. Juice samples were collected at regular intervals to examine the shelf life of the treated juice.

Physicochemical analysis

Determination of pH, titratable acidity, cloud value, and total soluble solids (TSS)

The pH of the blended juice was tested using a digital pH meter by following the technique defined in procedure No. 31.203 of the Association of Analytical Chemists (AOAC, 2012). The titratable acidity of blended juice was evaluated according to the methodology established by Geremias-Andrade *et al.* (2019). The blended juice samples were titrated with 0.1-N NaOH, with 2–3 drops of phenolphthalein as an indicator, until the endpoint of pink color was attained. The proportion of titratable acidity was subsequently determined using the following equation:

$$\text{Acidity (\%)} = \frac{\text{NaOH used} \times 0.045}{\text{Weight of sample}} \times 100.$$

The total contents of soluble solids of the blended juice was assessed at ambient temperature utilizing a refractometer (Bellingham + Stanley Eclipse handheld refractometer, Fischer Scientific, Loughborough, UK) in accordance with the methodology established by Geremias-Andrade *et al.* (2019). A small quantity of blended juice was applied to the refractometer's prism, and the device was calibrated according to the manufacturer's specifications to measure TSS. On the other hand, the techniques established by Ozen *et al.* (2024) were used to determine the juice's cloud value. The amount of light absorbed or dispersed by the juice's suspended particles was measured to calculate the cloud value. Traditionally, this is accomplished by centrifuging the juice to separate particles, and then a spectrophotometer is used to measure the absorbance of the liquid that remained after centrifugation, known as supernatant.

Phytochemical analysis

Determination of total phenolic contents

The Folin–Ciocalteu technique, with some modifications, was used to quantify (TPC) in cantaloupe–sugarcane-blended juice sample (Dhansu *et al.*, 2023). First, 0.5-mL aliquots of juice extract was combined with 2.5 mL of Folin–Ciocalteu reagent. A reagent blank was created in lieu of a sample. Following 5 min incubation at ambient temperature, 1 mL of 7.5% sodium carbonate (Na_2CO_3) solution was added. Samples were incubated at ambient temperature for 1 h in the absence of light, and the absorbance was recorded at 765 nm relative to blank. TPC was determined using the calibration curve of gallic acid and represented as gallic acid equivalent (GAE) in milligrams per 100 mL of the sample (mg GAE/100 mL).

Determination of total flavonoid contents

The technique adopted by Hussain *et al.* (2025) was applied with slight modifications to ascertain the TFC of the blended juice. The diluted juice samples (250 µL) were combined with 75 µL of sodium nitrite (10%). Subsequently, 150 µL of aluminum chloride and 500 µL of sodium hydroxide (1 M) were added. The absorbance of the aforementioned combination was measured at 510 nm utilizing a spectrophotometer following the addition of 9 mL of distilled water. The results were quantified as milligrams of catechin equivalent (CE) per 100 mL of juice (CE/100 mL).

Determination of total flavanol contents

Total flavonol content in cantaloupe–sugarcane-blended juice was quantified using the methodology outlined by Nawaz *et al.* (2019), with slight changes. A juice extract based on pure ethanol (100 µg/mL) was prepared. Then 0.5 mL of the juice extract was placed in a glass cuvette, followed by the addition of 0.5 mL of 20% aluminum chloride and 1.5 mL of 10% sodium acetate. The sample was retained in darkness for 2.5 h and then examined. Absorbance was recorded at 440 nanometers (nm). Different amount of quercetin was applied to generate a standard curve of quercetin equivalent (QE), given in milligrams of quercetin per 100 mL of juice (mg QE/100 mL).

Determination of ascorbic acid

The concentration of ascorbic acid (mg/100 mL) in the blended juice were determined by titration method with a standardized solution of 2,6-dichlorophenol indophenol dye, as outlined in the method described by Hussain *et al.* (2024b).

2,2-Diphenyl-1-picrylhydrazyl (DPPH) free radical scavenging activity

Kinnow juice samples were evaluated for DPPH free radical scavenging activity by applying the technique adopted by Iqbal *et al.* (2023), with minor modifications. The below-mentioned equation was used to determine variation in absorbance:

$$\text{DPPH free radical scavenging activity} = \frac{A_0 - A_1}{A_0} \times 100,$$

where A_0 is the absorbance of the control and A1 is the absorbance of extracts. A similar approach was used to evaluate DPPH radical scavenging activity using Trolox as a reference, with findings expressed as µM equivalent of Trolox per mL of juice (µM Trolox/mL).

Microbial analysis

The blended juice was examined for yeast and mold, and total plate count (log colony-forming unit [CFU]/mL) of the blended juice during storage by adopting the procedure outlined by Siddique *et al.* (2023).

Sensory evaluation

The sensory characteristics of cantaloupe–sugarcane-blended juice were assessed by 30 professional panelists. The profile of cantaloupe–sugarcane-blended juice samples was developed through hedonic testing and quantitative descriptive analysis, incorporating various combinations of temperature and time intervals. The microbial safety of the samples was determined prior to sensory testing. The characteristics of color, flavor, taste, and the overall acceptability of the blended juice were assessed using a 9-point hedonic scale from “extremely disliked” (1 point) to “extremely liked” (9 points) (Hussain *et al.*, 2024a).

Statistical analysis

All analyses were conducted in triplicate to obtain mean values. The statistical analyses of the collected data were conducted using the Minitab 16 software by following the procedure established by Steel and Torrie (1981). The one-way ANOVA test was used to identify significant differences in mean values at probability, $p \leq 0.05$ (considered as statistically significant). Tukey’s test was used to identify significant differences among statistical values.

Results and Discussion

Effect of cold plasma on the pH of blended juice during storage

The pH values of cantaloupe–sugarcane-blended juice at different storage intervals under CP treatment are presented in Table 2. On day 0 of the storage, the highest pH value (5.32) was observed in Ar-treated (T2) sample, while lowest in positive control (CSJ+) (5.03). The pH values for all treatments except T2 showed a declining trend over time, suggesting progressive acidification of samples. The sample treated with Ar gas showed the highest

Table 2. Effect of cold plasma on the pH of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	5.03±0.05$^{g–i}$	5.01±0.01^{g,h}	4.99±0.01$^{h–j}$	4.95±0.01^{j,k}	4.89±0.01^{k}
CSJ0	5.20±0.10^{e,f}	5.17±0.02^{d,e}	5.11±0.02^{f,g}	5.02±0.02^{h,i}	4.92±0.02^{j,k}
T1	5.30±0.00$^{a–d}$	5.29±0.00$^{a–d}$	5.27±0.00$^{a–e}$	5.26±0.00$^{b–e}$	5.25±0.00$^{c–e}$
T2	5.32±0.00$^{a–d}$	5.33±0.00$^{a–d}$	5.35±0.00$^{a–c}$	5.36±0.00^{a,b}	5.39±0.00^{a}

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \le 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

pH values because the least fermentation was observed in this treatment, compared to both positive and negative controls as well as He-treated sample. At the end of storage period, maximum pH value was observed in T2 (5.39) sample and minimum in CSJ+ (4.89). Decrease in pH over time highlights the impact of both CP treatment and storage duration on the acidification process of the juice. This decline in pH suggests that storage duration played a crucial role in pH stability, with CP treatment influencing the rate of acidification. The results emphasize the interaction between gas type and storage period in maintaining the pH of juice, with Ar gas treatment (T2) showing maximum resistance to acidification. Scientific evidence shows that the pH values of juices decrease due to microbial processes and enzymatic reactions, which generate organic acids. Ma *et al.* (2024) observed similar trends during CP treatment of fruit juices. The measured pH reduction follows the same pattern as breaking down of carbohydrates into organic acids, as discovered by Su *et al.* (2019). Among all the treatments, the CP-treated samples (He-treated [T1] and T2) showed elevated pH values, while the pH of the negative control (CSJ0) decreased most significantly. Studies conducted by Nwabor *et al.* (2022) showed that CP reduced microbial activity levels together with enzymatic degradation, thus preserving pH stability. The Ar plasma treatment in T2 samples led to greater pH stability than He plasma treatment in T1 samples. According to the findings of Zhao *et al.* (2020), Ar plasma showed stronger antimicrobial effects that slowed acidification process. The assessment of CSJ+ beside CSJ0 demonstrates the effectiveness of techniques used for preservation of juice quality. It has been stated by Toy *et al.* (2022) that untreated juices demonstrate speedier pH decline through oxidation processes combined with natural fermentation. The research done by de Medeiros Dantas *et al.* (2023) reported that sugarcane juice developed progressive acidification after microbial fermentation caused by amelioration of lactic acid. The stable pH values in CP-treated samples indicate this technique's potential for becoming an efficient nonthermal preservation system, which reduces acidification caused by microbes.

Effect of cold plasma on total soluble solids of blended juice during storage

Table 3 shows that TSS is highly significant factor among treatments and storage durations. It is observed in Table 3 that TSS decrease in two treatments, except T2 and CSJ0. At the start of storage (day 0) minimum TSS (12.0) were observed in CSJ+, while maximum (12.32) was observed in T2. During storage period, it was observed that TSS elevated in T2 (12.32–12.40) at the end of storage period. This increase in TSS over time suggests possible water loss, concentration effects, or metabolic activity in juice matrix. The results indicated that CP treatment, particularly with Ar gas (T2), had a role in maintaining TSS stability, while CSJ0 exhibited the most pronounced increase in TSS. The current TSS value that changes with CP exposure presents identical results as the past results. According to Nachal *et al.* (2023), the TSS values tended slightly downward during storage period in CSJ+ because microbial activity depleted TSS. Research on untreated fruit juices demonstrates that aging of natural product leads to decreased sugar levels during storage period (Yue *et al.*, 2024). The increased TSS values in CSJ0 could be due to not treating the juice through CP, because the process normally lowers initial sugar content by creating reactive species generated by CP. The research done by Nanje Gowda *et al.* (2024) confirmed that nonthermal processing initiated small alterations in sugar composition, which resulted from the break down of polysaccharides or the Millard reaction. The TSS values in T1 and T2 remained steady because the CP method used in this research did not affect the TSS content of the blended juice substantially. Retention of TSS in T2 was higher than in T1, presumably because Ar plasma maintained sugar molecular structure as reported by Qin *et al.* (2021). Islam *et al.* (2024) established that He plasma-generated free radicals degrade juices slightly through sugar breakdown while measuring Brix values. The measurements of TSS indicate that gas selection and treatment length determine how much CP preserves or diminishes sugar content in CP-treated juices. Umair *et al.* (2022) confirmed that nonthermal plasma offers

Table 3. Effect of cold plasma on total soluble solids (%) of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	12.0±0.03^{i}	11.95±0.04^{i}	11.9±0.02^{ij}	11.87±0.03^{j,k}	11.8±0.06^{k}
CSJ0	12.3±0.00$^{f–h}$	12.5±0.00^{d}	12.8±0.06^{c}	13.1±0.10^{b}	13.5±0.06^{a}
T1	12.31±0.00$^{f–h}$	12.25±0.00$^{f–h}$	12.22±0.00^{g,h}	12.2±0.00^{g,h}	12.18±0.01^{h}
T2	12.32±0.00$^{f–h}$	12.33±0.01$^{e–h}$	12.35±0.01$^{e–g}$	12.38±0.01^{e,f}	12.4±0.01^{d,e}

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \leq 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

Table 4. Effect of cold plasma on the titratable acidity (%) of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	0.30±0.01^{j}	0.31±0.01^{j}	0.35±0.00^{i}	0.36±0.00^{i}	0.38±0.01^{h}
CSJ0	0.40±0.01^{f,g}	0.60±0.01^{d}	0.71±0.02^{c}	1.10±0.001^{b}	1.39±0.01^{a}
T1	0.40±0.00^{g,h}	0.41±0.00^{f,g}	0.43±0.00$^{e–g}$	0.46±0.00^{e,f}	0.48±0.00^{e}
T2	0.41±0.00^{g,h}	0.43±0.00^{f,g}	0.44±0.00$^{e–g}$	0.45±0.00^{e,f}	0.46±0.00^{e}

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \leq 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

varying effects on sugar stability based on operational parameters if used for treating fruit-based beverages. This research demonstrates that gas-dependent CP treatment produces minor but significant effects on the TSS values of cantaloupe–sugarcane-blended juice.

Effect of cold plasma on the titratable acidity of blended juice during storage

The titratable acidity results of blended juice at different storage intervals under CP treatment are presented in Table 4. Results in Table 4 indicate that the titratable acidity of blended juice escalated during storage period. The maximum increase was observed in CSJ0, ranging from 0.40 to 1.10. At the start of storage, the lowest titratable acidity was observed in CSJ+ (0.30). After 120 days of storage, acidity values were more pronounced in positive and negative control treatments. Titratable acidity was stable in CP-treated blended juice sample, and more stability was observed in T2. A study done by Mendes Ferreira and Mendes-Faia (2020) supports these findings, as they report that organic acids develop in stored foods because of enzyme activity and microbial metabolism (Wang *et al.,* 2025; Zhang *et al.,* 2024). The untreated juice (CSJ0) displayed the highest titratable acidity value because it underwent natural fermentation during storage. According to Roobab *et al.* (2018), untreated fruit juices had considerable acidity increase through microbial growth and enzymatic activities during storage periods. Titratable acidity values of samples treated using CP (T1 and T2) increased more slowly, compared to untreated juice samples because CP treatment successfully controlled enzymatic functions and microbial growth. According to Mayookha *et al.* (2023), plasma treatment of fruit juices effectively inhibits microbial metabolism, which slows down the acid production. The acidity levels of juice samples treated with He and Ar plasmas (T1 and T2) stayed at lower levels, compared to untreated juice sample (CSJ0). These findings was also supported by the results of Ozen and Singh (2020), indicating that plasma technology provides juice preservation benefits through minimal physicochemical changes. The research done by Petruzzi *et al.* (2017) revealed that juice acids remained more stable in minimally processed products than in those without any treatment. Multiple studies have shown that the selected gas type for plasma treatment affects the levels of titratable acidity variation (López *et al.*, 2019).

Effect of cold plasma on ascorbic acid of blended juice during storage

The vitamin C content of blended juice at different storage intervals under CP treatment is presented in Table 5. On day 0, the vitamin C content was maximum in CSJ0 (40.9±0.06 mg/100 mL), followed by T2

Table 5. Effect of cold plasma on the ascorbic acid (mg/100 mL) of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	38.8±0.10^{f}	36.0±0.15	31.2±0.07^{k}	26.2±0.21^{m}	20.4±0.10^{o}
CSJ0	40.9±0.06^{a}	34.1±0.10	29.1±0.21^{l}	23.1±0.10^{n}	16.6±0.15^{p}
T1	40.4±0.07^{b,c}	39.5±0.10^{e}	38.5±0.12^{f}	37.5±0.00^{g}	36.6±0.10^{h}
T2	40.7±0.06^{a,b}	40.5±0.08^{b,c}	40.3±0.05^{c,d}	40.2±0.03^{c,d}	40.0±0.19^{d}

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \leq 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

(40.7±0.06 mg/100 mL), while CSJ+ had the lowest initial value (38.8±0.10 mg/100 mL). Over the storage period, all treatments exhibited a continuous decline in vitamin C levels, with the most substantial reduction observed in CSJ0, reaching the lowest value of 16.6±0.15 mg/100 mL on day 120. Similarly, CSJ+ also showed a significant decrease, with vitamin C content reducing to 20.4±0.10 mg/100 mL by the end of storage. In contrast, CP-treated samples (T1 and T2) maintained significantly higher vitamin C levels, with T2 retaining maximum rank (40.0±0.19 mg/100 mL). Vitamin C contents showed a significant decline from the start to the end of storage. The results presented in Table 5 suggest that CP treatment, particularly with Ar gas (T2), effectively preserved vitamin C content during storage, whereas the untreated controls (CSJ0 and CSJ+) exhibited the most significant losses. According to Doseděl *et al.* (2021), destruction of vitamin C occurs mainly because the nutrient responds negatively to oxygen exposure along with light and temperature. According to the results of the current study, vitamin C levels in CSJ0 decreased faster than in the treated juice samples; this supports the conclusions of the study done by Giannakourou and Taoukis (2021) about minimal processing methods preserving vitamin C through reduced oxidation mechanisms. Vitamin C content in T1 and T2 samples maintained better stability during storage period through CP treatment, compared to the control juice samples. Retention of vitamin C in T2 (Ar-treated sample) appears better than in the untreated juice sample (CSJ0) because gas composition during CP treatment impacts ascorbic acid stability, as also demonstrated by other studies (Zargarchi *et al.*, 2024). According to the reports of Zargarchi *et al.* (2024), reactive species from plasma may have integrated with juice components, thus limiting the oxidation-induced degradation. Vitamin C degradation during storage in the untreated sample showed comparable results to the findings of Xanthakis *et al.* (2018), who indicated that vitamin C degradation follows the first-order kinetics based on oxygen availability and temperature changes.

Effect of cold plasma on the cloud value of blended juice during storage

The cloud value of blended juice at different storage intervals under CP treatment is presented in Table 6. On day 0, maximum cloud value was observed in T2 (1.51±0.29%) and minimum in T1 (0.90±0.01%). Over the time, all treatments exhibited a gradual decline in cloud value, with the most substantial decrease observed in CSJ0, reaching the lowest cloud value of 0.88±0.01% on day 120. Similarly, CSJ+ showed a significant decrease to 0.61±0.00% by the end of storage. In contrast, CP-treated samples (T1 and T2) maintained higher cloud stability, with T2 retaining the maximum stability (0.82±0.01%). This decrease suggests sedimentation of suspended particles, aggregation of pulp, and structural changes in juice components over storage. The results indicate that CP treatment, particularly with Ar gas (T2), effectively maintained cloud stability, while the untreated controls (CSJ0 and CSJ+) exhibited greater losses in turbidity. The preservation of fruit juice's cloud stability is achieved through CP treatment, which, according to a prior research, inactivates pectin methylesterase (Umair *et al.*, 2022). The CSJ0 demonstrated the lowest cloud value (0.69±0.02) because sedimentation and particle aggregation was substantial throughout the experiment period. A continual decrease in cloud stability occurs in the untreated fruit juice samples, as documented by Umair *et al.* (2022). The He gas treatment for 90 s in T1 produced better cloud value retention (0.79±0.04), compared to the untreated control samples. This indicates that He-based CP shows a moderate effect on cloud stability because He generates fewer reactive species, compared to Ar-based plasma (Bolouki *et al.*, 2019). Past research confirms that the observed cloud value changes between treatments because CP modifies surface charges and reduces microbial activity together with altering particle dispersion and colloidal stability (Bolouki *et al.*, 2019). Stability of juice cloud under Ar-based CP treatment (T2) is superior, because the technology's higher ionization energy allows more efficient modification of juice components

Table 6. Effect of cold plasma on the cloud value (%) of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	0.94±0.00[b]	0.93±0.00[b]	0.92±0.00[b]	0.91±0.00[b]	0.61±0.00[c]
CSJ0	0.93±0.00[b]	0.92±0.00[b]	0.90±0.00[b]	0.89±0.00[b]	0.88±0.01[b]
T1	0.90±0.01[b]	0.86±0.01[b]	0.83±0.01[b]	0.80±0.01[b,c]	0.77±0.01[b,c]
T2	1.51±0.29[a]	0.89±0.01[b]	0.86±0.01[b]	0.84±0.01[b]	0.82±0.01[b]

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \leq 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

to inhibit precipitation and decline in turbidity (Nehmé *et al.*, 2024). The research discovers that CP features potential of an effective nonthermal approach that safeguards the quality characteristics of blended juices throughout storage periods.

Effect of cold plasma on DPPH free radical scavenging activity of blended juice during storage

The results of antioxidant potential in the form of DPPH free radical scavenging activity of blended juice at different storage intervals under CP treatment are presented in Table 7. On day 0, the highest DPPH free radical scavenging activity was observed in T2 (88.1±0.10 μg ascorbic acid equivalent [AAE]/mL), followed by T1 (84.8±0.29 μg AAE/mL), while the lowest initial value was recorded for CSJ0 (71.5±0.50 μg AAE/mL). Over storage, all treatments exhibited a gradual decline in the DPPH free radical scavenging activity, with the most pronounced decrease observed in CSJ0, reaching the lowest value of 23.3±0.76 μg AAE/mL on day 120. Similarly, CSJ+ also showed a significant decrease, with antioxidant activity decreasing to 33.4±0.45 μg AAE/mL by the end of storage. In contrast, CP-treated samples (T1 and T2) retained significantly higher DPPH free radical scavenging activity, with T2 maintaining the maximum activity (79.2±0.10 μg AAE/mL). The results indicate that CP treatment, particularly with Ar gas (T2), effectively preserved the antioxidant potential of juice, while the untreated controls (CSJ0 and CSJ+) exhibited the most significant losses in the DPPH free radical scavenging activity. The antioxidant properties in CP-treated juice increased due to formation of reactive species from plasma that activated phenolic compounds and other bioactive molecules (Zargarchi *et al.*, 2024). Over the storage period, decrease in DPPH free radical scavenging activity became significant, especially in the control samples through the combined effect of ascorbic acid and polyphenol degradation from enzyme-mediated oxidation. Zia *et al.* (2024) also established similar findings, when they tested fruit juices without thermal treatment versus those processed using nonthermal methods. According to Punia Bangar *et al.* (2022), the application of CP treatment results in modified chemical structures that enable better stability during storage periods. The superior activity of Ar plasma (T2) over He plasma (T1) during juice processing might result from differences in plasma reactions along with their effects on juice components because Ar produces more reactive species that benefit antioxidant preservation (Wang *et al.*, 2025). Research conducted by Liu *et al.* (2019) supports how storage duration cause juice oxidization, leading to reduced free radical scavenging activity (Aktı and Yildiz, 2025). The DPPH free radical scavenging activity is initially benefited from the presence of antioxidants in fresh juice samples, but such benefits decrease over time because of natural breakdown of these bioactive compounds. Research done by Boateng, (2024) proved that nonthermal processing helps to diminish the breakdown of bioactive compounds, so continuing the higher levels of antioxidant capacity for longer durations.

Effect of cold plasma on total phenolic content of blend juice during storage

The results of TPC of blended juice samples at different storage intervals under CP treatment are presented in Table 8. On day 0, the TPC values were maximum in T2 (152.27±0.25 mg GAE/100 mL), followed by T1 (144.73±0.25 mg GAE/100 mL), while the minimum initial value was observed in CSJ0 (131.26±0.59 mg GAE/100 mL). Over the storage, all treatments exhibited a gradual decline in TPC, with the most pronounced decrease observed in CSJ0, reaching the lowest value of 51.67±0.61 mg GAE/100 mL at day 120. Similarly, CSJ+ also showed a significant decrease, with TPC content decreasing to 57.37±1.13 mg GAE/100 mL by the end of storage period. In contrast, CP-treated samples (T1 and T2) retained significantly higher TPC levels, with T2 maintaining the maximum level (139.23±0.20 mg GAE/100 mL). This decrease was likely due to oxidative degradation and polymerization reactions during storage. The results suggest that CP treatment, particularly with

Table 7. Effect of cold plasma on DPPH free radical scavenging activity (µg AAE/mL) of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	71.5±0.50[h]	66.7±0.64	58.5±0.71[k]	44.6±0.56[l]	33.4±0.45[n]
CSJ0	74.3±0.32[g]	60.6±0.29	43.5±0.40[l]	35.0±1.00[m]	23.3±0.76[o]
T1	84.8±0.29[b]	81.5±0.50[d]	79.5±0.50[e]	76.9±0.21[f]	74.2±0.10[g]
T2	88.1±0.10[a]	85.3±0.27[b]	83.1±0.15[c]	81.2±0.10[d]	79.2±0.10[e]

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \leq 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

Table 8. Effect of cold plasma on the total phenolic content (mg GAE/100 mL) of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	131.67±0.15[h]	121.43±0.56	106.40±0.14[k]	84.20±026[m]	57.37±1.13[o]
CSJ0	131.26±0.59[h]	110.100±0.27	85.46±0.32[l]	63.76±0.40[n]	51.67±0.61[f]
T1	144.73±0.25[c]	140.200±0.10[e]	136.93±0.38[f]	134.100±0.10[g]	130.90±0.10[h]
T2	152.27±0.25[a]	148.17±0.15[b]	145.17±0.15[c]	142.13±0.15[d]	139.23±0.20[e]

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \leq 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

Ar gas (T2), effectively preserved phenolic compounds in the juice, while the untreated controls (CSJ0 and CSJ+) exhibited maximum significant losses. Previous research done by Zargarchi and Esatbeyoglu, (2024) supported the current findings by showing that CP treatment improves TPC through alterations in cell wall structure, which lead to release of phenolic compounds. Following plasma treatment, juice molecules contact reactive species, which break down polyphenolic complexes into basic simpler antioxidants (Fernandes and Rodrigues, 2021). The TPC content showed a substantial decrease throughout storage in each sample, yet control samples, CSJ+ and CSJ0, experienced maximum decrease. The degradation of phenolic compounds through oxidative processes during storage is thoroughly observed in scientific studies, and the following three factors cause this process: enzymatic activity, oxygen exposure, and polymerization reactions (Ali *et al.*, 2022). Previous research showed that TPC levels initially increased following nonthermal CP technology but later decreased (Kumar *et al.*, 2023). Phenolic compounds in T1 and T2 after plasma treatment remained more stable than in control samples because the plasma activated enzymes and reduced microorganisms, prolonging the resistance against oxidation degradation (Punia Bangar *et al.*, 2022). The retention of phenolic compounds reached its maximum level in T2 (Ar plasma), resulting in better stability, compared to He plasma treatment probably because Ar has higher ionization energy as well as generates different reactive species (Zhou *et al.*, 2024). The preservation of bioactive compounds in fruit juices through Ar-based plasma treatment is documented as effective, compared to other gases in previous research (Chen *et al.*, 2022). Delivery of CP elevated TPC levels in the beginning, but did not alter the typical degradation of phenolic compounds that occurs naturally. According to previous research findings on plasma-based beverage preservation, different plasma gas treatments showed varying levels of phenolic compound retention, which demonstrates how composition of plasma gas affects the stability of biological compound in fruit-based beverages Zhu *et al.* (2023) and Kumar *et al.* (2023).

Effect of cold plasma on the total flavonoid content of blended juice during storage

Table 9 shows that TFC values (mg CE/100 mL) of the blended juice are significantly different among different treatments. On day 0, the highest TFC was observed in T2 (56.54±0.21 mg CE/100 mL), followed by T1 (53.83±1.86 mg CE/100 mL), while the lowest initial value was recorded for CSJ+ (51.20±0.20 mg CE/100 mL). Over storage, all treatments exhibited a gradual decline, with the most pronounced decrease observed in CSJ0, achieving the lowest value of 39.50±0.20 mg CE/100 mL on day 120.

Table 9. Effect of cold plasma on the total flavonoid content (mg CE/100 mL) of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	51.20±0.20^{c,d}	49.47±0.38^{d,e}	48.10±0.00$^{e–g}$	46.33±0.06^{g}	42.57±0.12
CSJ0	51.33±0.12^{c,d}	48.60±0.26^{e,f}	46.20±0.10^{g,h}	44.10±0.10^{h}	39.50±0.20
T1	53.83±1.86^{b}	51.48±1.48^{c,d}	50.37±0.64^{d,e}	47.04±0.98^{f,g}	44.07±0.98^{h}
T2	56.54±0.21^{a}	54.57±0.57^{a,b}	52.59±0.37^{b,c}	50.0±0.37^{d,e}	46.54±0.56^{f,g}

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \leq 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

Similarly, CSJ+ also showed a significant decrease, with TFC reducing to 42.57±0.12 mg CE/100 mL by the end of storage. In contrast, CP-treated samples (T1 and T2) retained significantly higher TFC levels, with T2 maintaining the maximum level (46.54±0.56 mg CE/100 mL). The overall mean TFC at the start of storage was 53.25±2.42 mg CE/100 mL, which significantly declined to 43.17±2.71 mg CE/100 mL by day 120 (Table 9). This decrease can be attributed to the oxidation-induced degradation of flavonoids during storage. The results indicate that CP treatment, particularly with Ar gas (T2), effectively preserved TFC in juice, while the untreated controls (CSJ) and CSJ+) exhibited the most significant losses. The retention of TFC proved better under Ar-based plasma treatment (T2), compared to He-based treatment (T1), because Ar provided higher efficiency combined with lower oxidative changes during the treatment process based on previous research (Rodríguez *et al.*, 2019). According to Tripathy and Srivastav (2024), CP treatment led to superior bioactive compound preservation because the TFC levels were elevated in CP-treated samples, compared to control samples. Control samples, CSJ0 and CSJ+, showed rapid TFC degradation, compared to CP-treated samples, because, according to Umair *et al.* (2022), enzymatic oxidation often catalyzed by polyphenol oxidase occurred more intensively in untreated juice samples. Additional preservatives integrated into the CSJ+ treatment led to higher flavonoid stability, compared to CSJ0, demonstrating that external additives help to preserve phytochemical stability. Scientific evidence confirms that TFC degradation in fruit-based beverage depends heavily on storage conditions and temperature beside oxygen content (Enaru *et al.*, 2021). Results of the current study demonstrate that Ar plasma treatment excels as a potential nonthermal preservation technology for preserving stable flavonoids in mixed fruit beverages. Findings of the present research confirm plasma technology's advantages for preserving valuable compounds in fruit products, corresponding experimental results presented by Chen *et al.* (2020).

Effect of cold plasma on total flavanols of blended juice during storage

The results of total flavanols of blended juice at different storage intervals under CP treatment are presented in Table 10. Total flavanol values exhibited a decreasing trend over time, indicating progressive degradation of total flavanol compounds because of the interactions with other juice components. On day 0, the highest total flavanol content was observed in CSJ+ (12.54±0.00 mg QE/100 mL), followed by CSJ0 (12.20±0.01 mg QE/100 mL), while the lowest initial value was recorded for T1 (11.50±0.01 mg QE/100 mL). Over storage, all treatments exhibited a gradual decline, with the most pronounced decrease observed in CSJ0, reaching the lowest level of 10.20±0.10 mg QE/100 mL on day 120. Similarly, CSJ+ also showed a significant decrease, with total flavanol content reducing to 11.12±0.02 mg QE/100 mL by the end of storage. In contrast, CP-treated samples (T1 and T2) retained significantly higher flavanol levels, with T2 maintaining the maximum level (11.51±0.01 mg QE/100 mL). The results indicate that CP treatment, particularly with Ar gas (T2), effectively preserved flavanols content in the juice, while the untreated controls (CSJ0 and CSJ+) exhibited the most significant losses. The storage period led to a steady decrease of total flavanols because of flavonoid compound degradation caused by polyphenol oxidase (ElGamal *et al.*, 2023). The analysis of CSJ+, T1, and T2 samples beside CSJ0 indicated that CP treatment successfully preserved significant amounts of flavanols, thus demonstrating its potential as a bioactive compound protecting method. Research showed that CP applications caused alterations in the polyphenolic compounds that resulted in increased stability for some compounds despite neutral and beneficial impacts on others (Heydari *et al.*, 2023). The application of Ar-based CP (T2) generated maximum retention of flavanols during storage, followed by He-based plasma treatment (T1). Researchers had confirmed that exposing food to CP treatment reduced flavonoid degradation indicators, because plasma technology inactivated enzymes and

Table 10. Effect of cold plasma on the total flavanols (mg QE/100 mL) of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	12.54±0.00[a]	12.18±0.05[b]	12.12±0.03[b]	11.70±0.18[c,d]	11.12±0.02[i]
CSJ0	12.20±0.01[b]	11.80±0.02[c]	11.32±0.02[h]	11.07±0.02[i]	10.20±0.10[j]
T1	11.50±0.01[e-g]	11.46±0.01[e-h]	11.43±0.00[f-h]	11.40±0.00[f-h]	11.36±0.00[g,h]
T2	11.57±0.00[d,e]	11.56±0.00[d,e]	11.55±0.00[d-f]	11.52±0.00[e,f]	11.51±0.01[e-g]

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \leq 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

minimized microbial growth (Mayookha *et al.*, 2023). Other researchers reported different total flavanol values because they used varied fruits, storing conditions, and processing parameters. The research demonstrated that flavanols levels depended on various factors, including the fruit type and its natural phenolic chemicals as well as susceptibility to deterioration, because of the different storage and processing conditions (Liu *et al.*, 2021). The retention levels of bioactive compounds are especially influenced by three factors, which include gas type, exposure time, and flow rate in CP applications. Mkhari *et al.* (2025) validated these findings by reporting that controlled CP exposure preserved flavanol integrity but excessive CP provided an atmosphere conducive to bio-compound break down from reactive oxygen species formation. The total flavanols quantity measured during this study demonstrated consistency with earlier scientific work because juice composition varied alongside alternate processing procedures, and a variety of storage conditions created slight variations. Studies showed that Ar-based CP treatment provided protection to flavanols in fruit-based beverages, thereby documenting plant-based food enhancements through plasma technology (Lisboa *et al.*, 2024).

Effect of cold plasma on the total plate count (log CFU/mL) of juice during storage

The microbial load of cantaloupe–sugarcane-blended juice at different storage intervals under CP treatment is presented in Table 11. On day 0, the lowest total plate count was observed in T2 (1.65±0.108 log CFU/mL), followed by T1 (1.94±0.050 log CFU/mL), while the highest initial value was recorded for CSJ0 (2.70±0.001 log CFU/mL). Over storage, all treatments exhibited a gradual increase in microbial load, with the most pronounced growth observed in CSJ0, reaching the highest level of 2.89±0.004 log CFU/mL on day 120. Similarly, CSJ+ also showed a significant increase, with microbial load rising to 2.72±0.008 log CFU/mL by the end of storage. In contrast, CP-treated samples (T1 and T2) maintained significantly lower microbial counts, with T2 exhibiting the lowest microbial load (2.06±0.020 log CFU/mL) on day 120. During storage, increasing trend of microbial load was observed in all treatments. This increase in microbial load suggested microbial proliferation over time, although CP treatment significantly slowed the rate of growth. The results indicated that CP treatment, particularly with Ar gas (T2), effectively reduced microbial proliferation in the juice, while the untreated controls (CSJ0 and CSJ+) exhibited maximum microbial counts during storage. The results of He (T1) treatment testing versus Ar (T2) treatment replicates earlier scientific findings, which show plasma gases have varying antimicrobial effectiveness. Scientific studies done by Wenske *et al.* (2020) showed that Ar-based CP produced stronger reactive species than He-based plasmas, thus showing better microbe-killing potential. The total plate count values of T2 consistently remained lower than T1, which proved that plasma gas selection influenced the effectiveness of CP treatment. The research study supports the previous work by proving that CP functions effectively to decrease microbial count in fruit juices through nonthermal treatment. The differences observed in total plate count values, compared to other research studies, might stem from discrepancies in juice composition together with plasma treatment settings. Furthermore, microbial levels and storage conditions also influence antimicrobial dynamics (Thirumdas *et al.*, 2018).

Effect of cold plasma on the yeast and mold counts of juice during storage

The yeast and mold count results of cantaloupe–sugarcane-blended juice at different storage intervals under CP treatment are presented in Table 12. On day 0, the lowest yeast and mold counts were observed in T2 (1.41±0.163 log CFU/mL), followed by T1 (1.82±0.085 log CFU/mL), while the highest initial value was recorded for CSJ0 (2.60±0.006 log CFU/mL). Over storage, all treatments exhibited a gradual increase in yeast and mold counts, with the most pronounced growth observed in CSJ0,

Table 11. Effect of cold plasma on the total plate count (log CFU/mL) of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	2.38±0.003f,g	2.48±0.007f	2.60±0.012e	2.66±0.010d,e	2.72±0.008c-e
CSJ0	2.70±0.001c-e	2.73±0.004b-d	2.78±0.007a-c	2.84±0.001a,b	2.89±0.004a
T1	1.94±0.050j,k	2.04±0.027h-j	2.11±0.013h	2.15±0.012h	2.33±0.010g
T2	1.65±0.108l	1.72±0.097l	1.86±0.030k	1.96±0.029i-k	2.06±0.020h,i

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \leq 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

Table 12. Effect of cold plasma on the yeast and mold counts (log CFU/mL) of blended juice during storage.

Treatment	Days				
	0	30	60	90	120
CSJ+	2.32±0.002e,f	2.45±0.005d,e	2.50±0.008c,d	2.60±0.009b-d	2.66±0.015a–c
CSJ0	2.60±0.006a–d	2.69±0.012a,b	2.70±0.008a,b	2.77±0.004a	2.77±0.004a
T1	1.82±0.085h,i	1.84±0.014g–i	1.99±0.010g,h	2.00±0.008g	2.18±0.018f
T2	1.41±0.163l	1.53±0.111k,l	1.64±0.108j,k	1.80±0.035i,j	1.92±0.026g–i

Notes: Mean values having the same superscript letters in a column or in a row are statistically nonsignificant ($p \leq 0.05$). Within box means express interaction means. CSJ0: negative control; CSJ+: positive control; T1: He-treated sample; T2: Ar-treated sample.

reaching the highest value of 2.77±0.004 log CFU/mL on day 120. Similarly, CSJ+ also showed a significant increase, with yeast and mold counts rising to 2.66±0.015 log CFU/mL by the end of storage. In contrast, CP-treated samples (T1 and T2) maintained significantly lower yeast and mold counts, with T2 exhibiting the lowest yeast and mold counts (1.92±0.026 log CFU/mL) on day 120 (Table 12). This increase suggests fungal proliferation over time, although CP treatment significantly slowed the rate of growth. The results indicated that CP treatment, particularly with Ar gas (T2), effectively reduced yeast and mold counts in the blended juice, while the untreated controls (CSJ0 and CSJ+) exhibited the highest yeast and mold growth during storage. Previous studies support the high initial mold count found in unprocessed juice samples because both sugarcane and cantaloupe juices create optimal fungal growth conditions because of their nutrient-rich composition (Okoye and Abba, 2024). Results from the previous research proved that unprocessed fruit juices tend to accumulate more mold because of fermentable sugar content and room temperature storage environments (Lan *et al.*, 2023). The yeast and mold counts significantly decreased in juice samples treated with CP (T1 and T2) but the use of Ar gas treatment in T2 showed the strongest antifungal properties. The same mold-inhibiting results appeared in previous research about using CP to break fungal cell structures and stop spore germination in fruit beverages (Obileke *et al.*, 2022). Ar-based CP treatment proved more effective due to its enhanced energy characteristics, which led to the formation of increased reactive species according to the studies about nonthermal plasma destruction of microorganisms in liquid foods (Sunil *et al.*, 2018). Storage experiments on treated samples showed a steady growth of yeast and mold counts, which indicate that CP successfully reduced initial contamination, although its antimicrobial persistence reduced during this period (Nwabor *et al.*, 2022). The reported yeast and mold count values differ from those of other researchers, potentially because of variations in plasma treatment duration and the employed gases together with storage environment parameters. The literature demonstrated that optimizing plasma parameters concerned for specific juice matrices because, according to Ma *et al.* (2024), longer treatment periods or alternative gas combinations resulted in higher microbial elimination. The results of this research showed that CP remained a highly effective nonthermal method for germ elimination in fruit drinks, but demonstrated a requirement for optimal processing variables to maintain microbial safety.

Effect of cold plasma on the sensory properties of blended juice during storage

The color values of cantaloupe–sugarcane-blended juice at different storage intervals under CP treatment are presented in Figure 1. On day 0, the highest color value was

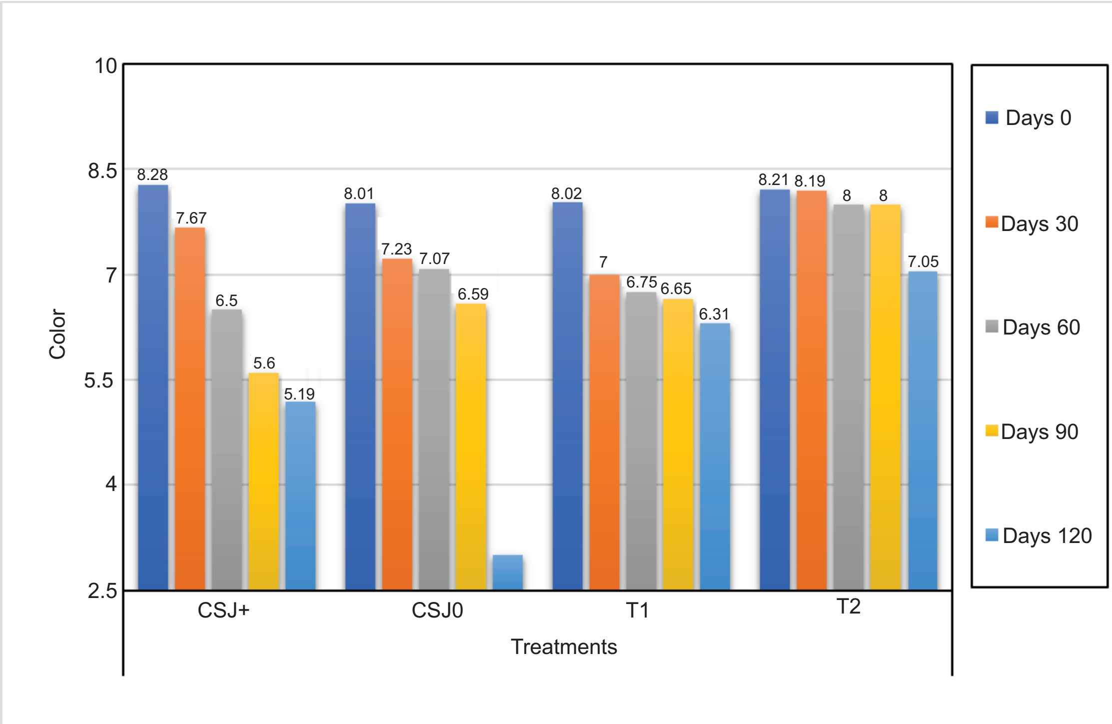

Figure 1. **Effect of cold plasma on the color of blended juice during storage.**

observed in T2 (8.21±0.20), followed by T1 (8.02±0.08), while the lowest initial color value was recorded for CSJ0 (7.00±0.38). Over the storage, all treatments exhibited a gradual decline in color scores, with the most pronounced decrease observed in CSJ0, reaching the lowest value of 4.70±0.40 on day 120. Similarly, CSJ+ also showed a significant decrease, with the color value reducing to 5.00±0.50 by the end of storage. In contrast, CP-treated samples (T1 and T2) retained significantly higher color values, with T2 maintaining the highest value (7.00±0.22). This decrease could be attributed to the break down of natural pigments, such as carotenoids and anthocyanins. The results indicate that CP treatment, particularly with Ar gas (T2), effectively preserved the color stability of the blended juice, while the untreated controls (CSJ0 and CSJ+) exhibited the most significant losses in color intensity. The results of the study done by Avîrvarei *et al.* (2023) agree with the present findings showing that CP methods successfully protect colors of fruit-based beverages by reducing their susceptibility to oxidative damage. T2 treatment displayed superior color retention because Ar played a key role in reducing enzymatic browning and pigment decay according to Nath *et al.* (2022), who showed that noble gases effectively stabilized natural pigments. The color evaluation data also confirmed the results of Umair *et al.* (2022), who observed major color changes in untreated juice samples during storage. Research done by Zargarchi *et al.* (2024) confirmed the current findings, which showed that CP improved the stability of carotenoids and polyphenols among fruit juices, thereby delaying browning reactions. According to Xu *et al.* (2022), non-thermal plasma treatments successfully limit pigment loss within test samples, compared to untreated control samples. The stable reactive environment produced by Ar gas may contribute to polyphenol oxidation limitations, which lead to color preservation. The present findings confirm previous research, which demonstrates the utility of CP as an innovative nonthermal approach to conserve the appearance of fruit-based beverage during storage.

The flavor evaluation of cantaloupe–sugarcane-blended juice at different storage intervals under CP treatment is presented in Figure 2. On day 0, the highest flavor score was observed in T2 (8.20±0.20), followed by T1 (8.00±0.30), while the lowest initial flavor value was recorded for CSJ0 (7.02±0.27). Over storage, all treatments exhibited a gradual decline, with the most pronounced decrease observed in CSJ0, reaching the lowest level of 4.00±0.40 on day 120. Similarly, CSJ+ also showed a significant decrease, with the flavor score reducing to 5.71±0.65 by the end of storage. In contrast, CP-treated samples (T1 and T2) retained significantly higher flavor scores, with T2 maintaining maximum score (7.20±0.30). This reduction is attributed to oxidative degradation of aromatic compounds and increasing acidity levels over

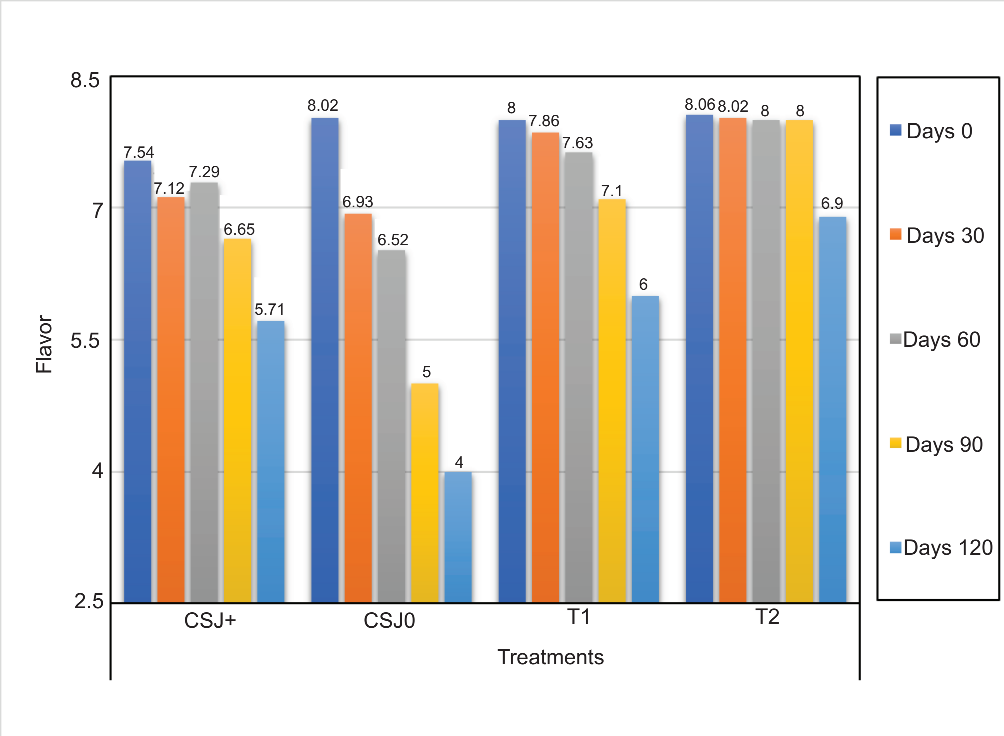

Figure 2. Effect of cold plasma on the flavor of blended juice during storage.

time. The results indicate that CP treatment, particularly with Ar gas (T2), effectively preserved the flavor quality of juice, while the untreated controls (CSJ0 and CSJ+) exhibited the most significant losses in sensory acceptability. Previous research showed that CP procedures effectively protected flavor compounds mainly through diminishing microbial actions and preventing oxidative damage (Jiang *et al.*, 2022).

The taste evaluation of blended juice at different storage intervals under CP treatment is presented in Figure 3. On day 0, the highest taste score was observed in T2 (8.10±0.01), followed by T1 (7.95±0.02), while the lowest initial value was recorded for CSJ0 (7.00±0.30). Over storage, all treatments exhibited a gradual decline, with the most pronounced decrease observed in CSJ0, reaching the lowest level of 4.00±0.38 on day 120. Similarly, CSJ+ also showed a significant decrease, with the taste score reducing to 5.00±0.00 by the end of storage. In contrast, CP-treated samples (T1 and T2) retained significantly higher taste scores, with T2 maintaining the highest level (7.00±0.04). This reduction is attributed to oxidative degradation of flavor compounds and increasing acidity levels over time. The results indicate that CP treatment, particularly with Ar gas (T2), effectively preserved the taste quality of the blended juice, while the untreated controls (CSJ0 and CSJ+) exhibited the most significant losses in sensory acceptability.

According to Korzeniowska *et al.* (2024), food products respond to CP treatment through modified volatile compounds. The overall acceptability of blended juice at different storage intervals under CP treatment is presented in Figure 4. On day 0, the highest overall acceptability score was observed in T2 (8.12±0.08), followed by T1 (8.01±0.04), while the lowest initial acceptability score was recorded for CSJ0 (7.50±0.15). Over storage, all treatments exhibited a gradual decline, with the most pronounced reduction observed in CSJ0, reaching the lowest level of 4.00±0.05 at day 120. This reduction could be attributed to oxidative degradation, increased acidity, and loss of desirable sensory characteristics over time. The results indicated that CP treatment, particularly with Ar gas (T2), effectively preserved the overall acceptability of the juice, while the untreated controls (CSJ0 and CSJ+) exhibited the most significant losses in sensory appeal. The sensory acceptability of mango juice treated by CP lasted longer than raw juice, thanks to its dual capacity for reducing microorganisms and preserving taste and nutritional elements (Palumbo *et al.*, 2022). According to Zhu *et al.* (2023), plasma treatment for orange juice resulted in superior protection of color, flavor, and the overall quality, compared to traditional thermal methods. Therefore, the implementation of CP with suitable selection of parameters is important to achieve optimum sensory quality of processed juices.

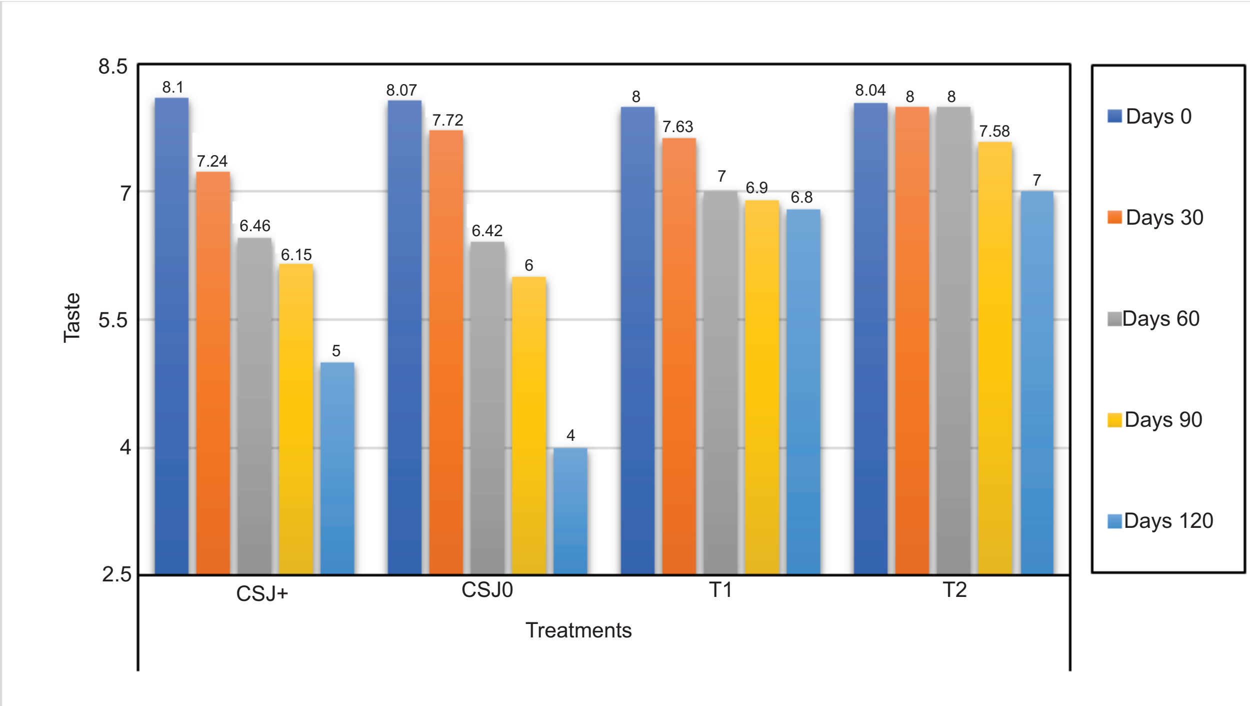

Figure 3. **Effect of cold plasma on the taste of blended juice during storage.**

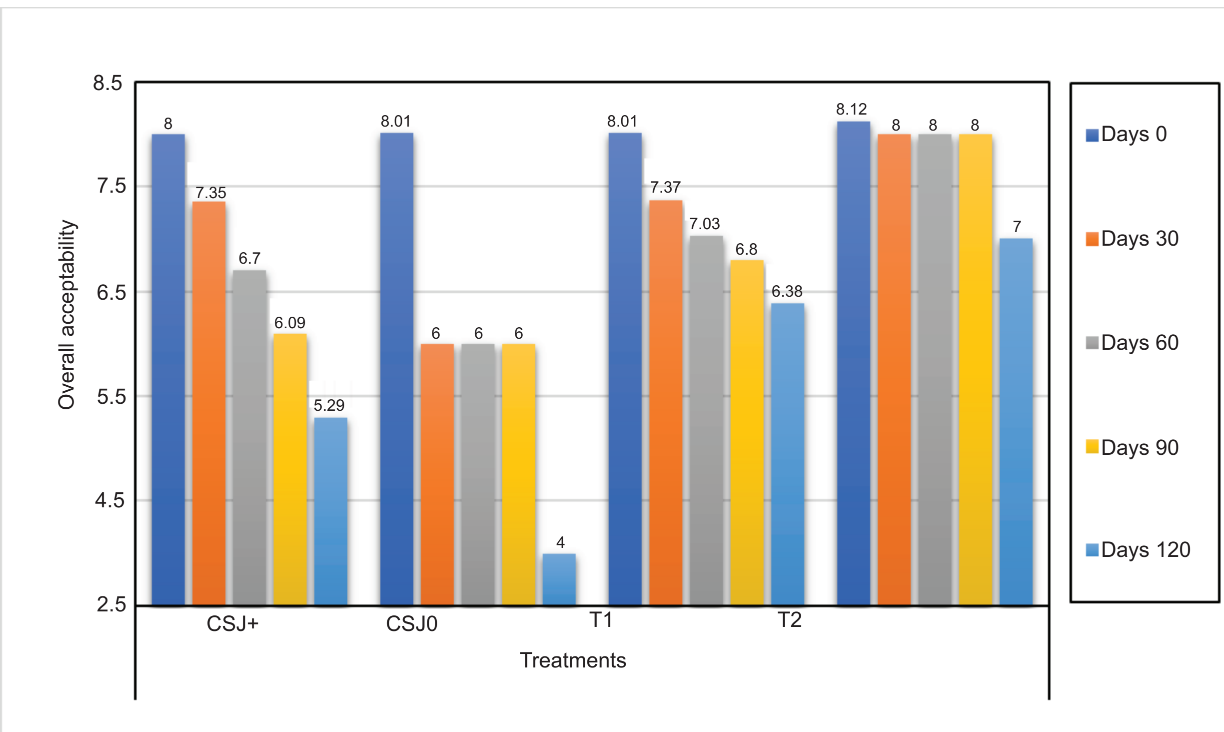

Figure 4. **Effect of cold plasma on the overall acceptability of blended juice during storage.**

Conclusion

Results of the present study revealed that cantaloupe–sugarcane-blended juice showed notable quality and safety improvements when CP technology was applied. The CP treatment successfully maintained physicochemical characteristics, retained phytochemicals, and decreased juice's microbial count. Accordingly, CP technology is a promising nonthermal fruit juice preservation technique with prospective uses in the food sector. The findings of the current study showed that two types of gases are used for CP generation to preserve blended juice. After reaction of CP with juice for specific period, it was observed that both inert gases are effective for preservation, compared to positive and negative controls. Between two inert gases, He and Ar, the most effective results were observed in the case of Ar gas throughout the storage period. Sensory analysis showed that application of CP was found suitable in improving the taste, color, flavor, and the overall acceptability of the blended juice. Additional study could investigate scalability for industrial applications and to optimize treatment conditions. These parameters can vary from product to product; better results could be achieved by optimization of plasma generation parameters (voltage, frequency and exposure time). This nonthermal technology can safeguard heat sensitive nutrients in food products as well as extend the shelf-life of products.

Data Availability

All data generated or analyzed in this study are included in the published article.

Conflict of Interest

The authors declared no conflict of interest.

Ethical Approval

The sensory evaluation was conducted in accordance with the guidelines for sensory studies as outlined by the Ethics Committee of Institute of Food Science and Human Nutrition, University of Sargodha, Pakistan, with the approval No. UOS/IFSN/2024/08. Individual informed consent was obtained from all participants included in the study.

Author Contributions

Conceptualization, Abdul Rehman; methodology, Muhammad Nadeem and Mian Anjum Murtaza; software, Nida Firdous; validation, Khairiah Mubarak Alwutayd and Fakhria A. Al-Joufi; formal analysis, Rizwan Arshad; investigation, Waqar Ali; resources, Ayaz Ali Khan; data curation, Fahad Al-Asmari; writing—original draft preparation, Abdul Rehman and Muhammad Nadeem.; writing—review and editing, Mian Anjum Murtaza; visualization, Ashiq Hussain; supervision, Ashiq Hussain and Inam ur Rahman.; project administration, Ashiq Hussain; funding acquisition, Inam ur Rahman.

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