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Antioxidant Potential and Quality Evaluation of Tea Prepared from Papaya (Carica papaya) Leaves

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ABSTRACT

Background: Papaya (*Carica papaya*) is a highly valued medicinal plant with significant bioactive properties. This research aims to evaluate the processing of papaya leaf tea, assess the impact of different processing methods on the quality of black tea, green tea, and instant tea. **Methods:** In this study, three types of tea - black tea, green tea, and instant tea - were prepared using papaya leaves. Initially, the bioactive compounds and antioxidant potential of both green and yellow papaya leaves were assessed. **Results:** Green papaya leaf powder (GLP) exhibited the highest concentrations of phenolic compounds (55.93±0.08 mg GAE/100 g), flavonoids (2192.93 mg QE/100 g), anthocyanins (282.66 mg/100 g), and antioxidant activity (182.86 mg TE/100 g). Green leaf paste (GLPa) and yellow leaf powder (YLP) also demonstrated significant levels of these compounds, while yellow leaf paste (YLPa) showed the lowest concentrations across all measurements. Black tea prepared from green papaya leaves contained the highest levels of phenolics (94.45 mg GAE/100 g), flavonoids (1026.24 mg QE/100 g), anthocyanins (1993.02 mg/100 g), and displayed the strongest DPPH inhibition (26.147%). While there were minor variations in the nutritional composition among the different tea types, they all exhibited similar profiles, with slight differences in ash and carbohydrate content. Sensory evaluation, using a 9-point hedonic scale and 10 panelists, revealed that black tea and green tea brewed for 2 minutes (B2) had the highest color intensity, flavor, taste, and acceptability compared to those brewed for 1 minute (B1) and 5 minutes (B3). **Conclusion:** These findings suggest that black tea made from green papaya leaves may offer the greatest health benefits due to its higher antioxidant content and activity compared to green tea and instant tea.

Introduction

Carica papaya, a member of the Caricaceae family, has long been used as a remedy for various diseases (Alabi *et al.*, 2012). In some Asian regions, young papaya leaves are steamed and consumed like spinach. Fresh green papaya leaves are considered antiseptic, while dried leaves

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are used as tonics and blood purifiers (Atta, 1999). Papaya leaves and fruit are rich in proteins and alkaloids, with notable pharmaceutical and medical applications, including anti-cancer properties (Rahmat *et al.*, 2002). Moreover, papaya leaf extracts have been found to increase platelet counts and shorten hospitalization during dengue fever (Yunita *et al.*, 2012), and they can be used as a complementary treatment for the disease. Phytochemical screening has identified bioactive compounds like saponins, cardiac glycosides, and alkaloids in papaya leaves, while tannins are absent. Green papaya leaves are rich in essential nutrients, while yellow papaya leaves are high in iron, suggesting their potential for use in herbal treatments and drug formulation (Ayoola and Adeyeye, 2010). Furthermore, papaya leaves have been shown to act as antihypertensive agents (Marie-Solange *et al.*, 2009). Young papaya leaves also possess antioxidant properties and can help lower blood pressure (Maisarah *et al.*, 2013).

Papaya leaf, known for its medicinal properties, can be processed into variety of functional food ingredients. Previous studies have highlighted papaya leaf tea's role in cancer prevention, with enzymes in the tea showing significant tumor-fighting potential (Otsuki *et al.*, 2010). Research has also shown that papaya leaf tea contains over 50 active ingredients that can kill fungi, parasites, bacteria, and cancer cells (McLaughlin, 2008). Additionally, papaya leaves are rich in vitamins A, C, and E, and contain vitamin B-17, which is used in traditional chemotherapy treatments. Papain, a digestive enzyme in papaya leaves, aids digestion and is most effective when the tea is brewed at high temperatures. Two types of papaya leaf tea can be made: green (fresh) and brown (dried). Green leaf tea is antiseptic, while brown leaf tea serves as a tonic and blood purifier (Atta, 1999). However, bioactive compounds in papaya leaves are susceptible to degradation, especially in their raw form. Powdering the leaves helps extend shelf life and simplifies handling (Ankita and Prasad, 2015).

Processing methods significantly affect the preservation of these compounds, and optimizing these methods is crucial for maintaining the quality of the final product (Lin *et al.*, 2012). Techniques like blanching and drying are commonly used to preserve plant materials, with recent innovations like freeze-drying and pulsed electric field (PEF) extraction improving the drying process (Parniakov *et al.*, 2016). Despite its widespread availability, papaya leaf has not been extensively explored for industrial use in Bangladesh. The processing of papaya leaf tea has not been previously studied, and there is limited information on its potential for commercial production. This research aims to evaluate the processing of papaya leaf tea, assess the impact of different processing methods on the quality of black tea, green tea, and instant tea, and determine the optimal brewing time for each type.

Materials and Methods

Chemicals and reagents

Ethanol and methanol (analytical grade) were used for extracting bioactive compounds from the papaya leaves. Folin-Ciocalteu reagent, quercetin, and gallic acid were used for quantifying phenolic compounds and flavonoids in the tea extracts.

Collection of papaya leaves

The experiment was conducted in the laboratory of the Department of Food Processing and Engineering, Chattogram Veterinary and Animal Sciences University. Fresh papaya leaves were collected in March 2024 from local trees in the Khulshi area of Chattogram, Bangladesh. Only fully mature, healthy leaves from the same maturity stage were selected for consistency. Two leaves were collected from each tree to ensure uniformity in the sample. The leaves were immediately transported to the laboratory for processing to preserve their bioactive properties. The leaves were thoroughly washed with distilled water to remove any dirt or contaminants before use in the experiment.

Processing of papaya leaf teas

*Black tea***:** Black tea was prepared following the procedure outlined by Dev & Iqbal (Dev and Iqbal, 2015), with minor modifications. Fresh papaya leaves were collected, washed with tap water, and left at room temperature for 2 hours in their raw state. The leaves were then shredded and weighed.

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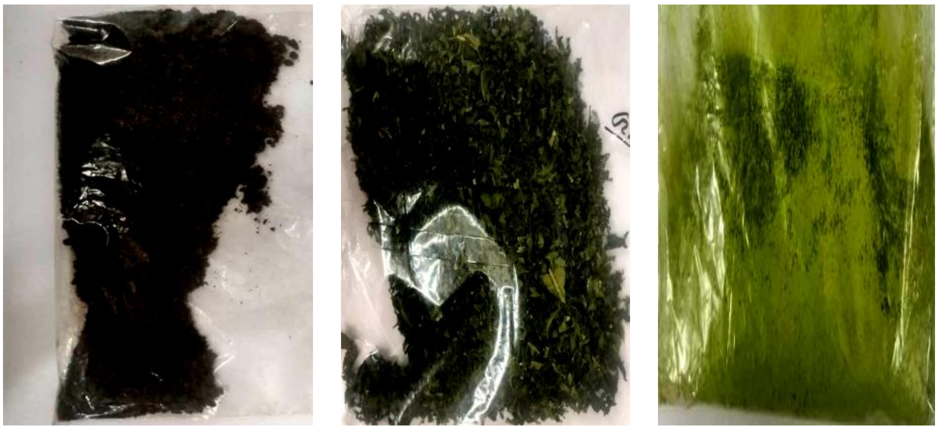
Next, the leaves were placed on trays inside a cabinet dryer and subjected to a temperature of 60 °C overnight to facilitate the fermentation process. Afterward, the trays were transferred to a hot air oven at 110 °C for 10 minutes to remove any remaining moisture. The leaves' mass was then measured to determine the crop yield. Finally, the leaves were hand-crushed, placed in polythene bags, and stored in a cool, dry place.

Green tea: Papaya green leaf tea is prepared by drying papaya leaves. Leaves of the same maturity stage were first harvested, washed, and stored at room temperature for 2 hours. The leaves were then steam blanched. To remove moisture, the leaves were placed on trays inside a cabinet dryer set at 80 °C for 24 hours. After drying, the leaves were uniformly cut and weighed. The trays were then transferred to a hot air oven set at 110 °C for 10 minutes to eliminate any remaining moisture. The mass of the leaves was measured to determine the yield. Finally, the leaves were gathered, sealed in polythene bags, and stored in a cool, dry place for preservation.

Instant tea: Prior to spray drying, the papaya leaf juice underwent two rounds of filtration to prevent clogging of the spray dryer atomizer. To reduce hygroscopicity, maltodextrin was used as a carrier material at a concentration of 6.0-10% w/v. Then the concentrated papaya leaf juice, mixed with maltodextrin was transferred to the spray drying system, with a feed flow rate of 350 mL/h and an internal temperature of 130 °C. The resulting papaya leaf powder was stored at room temperature.

Proximate analysis

The proximate composition of Papaya leaf and teas (**Figure 1**) obtained from papaya leaves were analyzed by prescribed method of AOAC (Association of Official Agricultural Chemists, 1931), using hot air oven, Kjeldahl assembly, and Muffle furnace, respectively.



Black tea **Green tea** **Instant tea**

Figure 1. Papaya leaf teas

Determination of bioactive compounds

Extract preparation

The preparation of the extract involved combining 20 ml of pure ethanol with 2 g of the sample in a Falcon tube, followed by a 72-hour incubation period. After 72 hours, the solvent was filtered and the resulting filtrates were gathered. Subsequently, the ethanolic extract was identified.

Measurement of total flavonoids content (TFC)

The samples' TFC was measured using the aluminum chloride colorimetric method reported by Chang *et al.* (Chang *et al.*, 2002). To create the extract stock solution with a concentration of 1 mg/ml, 1.5 ml of 95% C_2H_5OH was added to a test tube. This solution was then diluted in 0.5 ml portions. Afterward, 0.1 ml of a solution containing

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10% $AlCl_3$, 0.1 ml of a solution containing 1 mol/l potassium acetate, and 2.8 ml of distilled water were introduced into the test tube. The solution was allowed to stand at ambient temperature for 30 minutes. To fill the space, a corresponding amount of distilled water with 10% aluminum chloride was utilized. The measurement of absorbance was conducted using a UV-visible spectrophotometer at a specific wavelength of 415 nm (UV-2600, Shimadzu Corporation, USA). The total flavonoid concentration in the sample extracts was quantified by measuring their absorbance and comparing it to a standard quercetin curve. The outcome was quantified as the number of quercetin equivalents (QE) per gram of extract (mg QE/g) or TFC.

Measurement of total polyphenols content (TPC)

The Folin-Ciocalteu (FC) reagent method, as described by Al-Owaisi (Al-Owaisi *et al.*, 2014), was slightly modified to measure the TPC of the extracts. During this procedure, a 1 ml portion of ethanolic extract was combined with 1.5 ml of FC reagent in a falcon tube and allowed to sit at room temperature for duration of three minutes. Subsequently, 1.5 ml of a solution containing 7.5% Na_2CO_3 was introduced, and the resulting combination was left undisturbed for a duration of 60 minutes. The spectrophotometer (UV2600, Shimadzu Corporation, USA) was used to measure the absorbance at a wavelength of 765 nm, with C_2H_5OH serving as the blank reference. The TPC of the extracts was calculated by calculating the number of gallic acid equivalents (GAE) in milligrams per gram of extracts.

Measurement of total anthocyanins content (TAC)

The TAC of extracts was determined calorimetrically according to the method described by Selim (Selim *et al.*, 2008) with slight modifications. Three ml of each sample was pipetted into a cuvette, and the absorbance of the resultant solution was measured against a blank reagent (ethanol) at 520 using a UV-visible spectrophotometer (UV-1800, Shimadzu, Japan). TAC was calculated according to the following equation and expressed as milligrams of total anthocyanin per 100 g (mg TA/100g).

$$\text{TAC} = \frac{Absorbance\ of\ sample \times DF \times 100}{M \times E}$$

Where DF = Dilution factor; M = Weight of sample used to make a stock solution (g); E = Extinction coefficient (55.9)

Measurement of antioxidant capacity by DPPH assay

The antioxidant activity of the extracts was assessed using the DPPH assay, with minor adjustments to the protocol outlined by Azlim Almey *et al.* (Azlim Almey *et al.*, 2010). A solution of DPPH was prepared by dissolving approximately 6 mg of DPPH in 100 ml of pure methanol. Afterward, 1 ml of the methanolic extract was combined with 2 ml of the DPPH solution. The solution was delicately agitated and left undisturbed at ambient temperature in the absence of light for duration of 30 minutes. The absorbance at a wavelength of 517 nm was measured using a UV-VIS spectrophotometer. To establish control, a mixture of 1 ml of methanol and 2 ml of the DPPH solution was prepared, with methanol being used as the reference for comparison. To evaluate the scavenging activity of the samples, the reduction in absorbance compared to the DPPH standard solution was utilized as a measure. The extracts' antioxidant potential was assessed by measuring their ability to eliminate DPPH free radicals. A calibration curve was generated using TEAC composite (Trolox equivalent antioxidant capacity), which served as the standard as well. The results were quantified as milligrams of Trolox equivalents per gram of powder based on its dry weight (DW).

Sensory evaluation

The sensory evaluation was conducted by a panel of 10 trained panelists using 9 points hedonic scale. Panelists were selected based on their familiarity with the sensory characteristics of tea and other herbal beverages. All panelists were in good health and had no known allergies to the materials used in the study. They were instructed to refrain from consuming any strong-smelling food or drink, such as coffee or spicy food, at least one hour before participating in the sensory evaluation. A small

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amount of each tea sample (approximately 30–50 ml) was served in a standardized cup, and panelists were given a brief break between samples to cleanse their palate with water. The sensory scores were recorded for each attribute (color, aroma, taste, flavor, and acceptability) for all tea samples.

Data analysis

The data was organized, encoded, and documented in a Microsoft Excel 2019 spreadsheet. Data were analyzed using a one-way analysis of variance (ANOVA) to assess the differences between various treatments. Post-hoc comparisons were performed using the Fisher's LSD test to identify specific differences between groups. The significance level was set at p <0.05. All analyses were carried out using Minitab Statistical Software (Version 19.1).

Results

Bioactive compounds in papaya leaves

Table 1 presents the levels of four bioactive compounds in papaya leaves: total phenolic content (TPC), total flavonoid content (TFC), total anthocyanin content (TAC), and antioxidant activity (measured by DPPH inhibition). The green papaya leaf powder (GLP) showed the highest total phenolic content (55.93±0.08 mg GAE/100 g), followed by green leaf paste (GLPa) at 33.64±0.11 mg GAE/100 g, yellow leaf powder (YLP) at 19.42±0.13 mg GAE/100 g, and yellow leaf paste (YLPa) at 17.88±0.07 mg GAE/100 g. Table 1 showed that the greatest flavonoid concentration was found in GLP (2192.93 mg QE/100 g), followed by YLP (1452.78 mg QE/100 g), GLPa (1517.77 mg QE/100 g), and YLPa (791.25 mg QE/100). Anthocyanins were most concentrated in GLP (282.66 mg/100 g), while DPPH inhibition (a measure of antioxidant activity) was also highest in GLP (182.86 mg TE/100 g).

Table 1. Bioactive compounds in papaya leaves.

Sample	TPC (mg GAE/100 g)	TFC (mg QE/100 g)	TAC (mg/100 g)	DPPH (mg TE/100 g)
GLP	55.93±0.08[a]	2192.93±1.13	282.66±0.32	182.86±0.30
GLPa	33.64±0.11	1517.77±0.62	30.37±0.32	74.98±0.01
YLP	19.42±0.13	1452.78±0.65	89.99±1.74	20.50±0.08
YLPa	17.88±0.07	791.25±1.05	20.68±0.78	1.80±0.50

*[a]:Mean±SD, **GLP**: Green leaf powder, **GLPa**: Green leaf paste, **YLP**: Yellow leaf powder, **YLPa**: Yellow leaf paste, **TPC**: Total phenolic content, **TFC**: Total flavonoid content, **TAC**: Total anthocyanin content, **DPPH**: Antioxidant activity as the amount of DPPH*

Bioactive compounds in teas prepared from papaya leaves

Table 2 presents the levels of TPC, TFC, TAC, and antioxidant activity (measured by DPPH inhibition) in papaya leaf teas. The data indicates significant differences between black tea, green tea, and instant tea, which can be attributed to both the tea preparation method and the initial composition of the papaya leaves used. Among tea types, black tea had the highest levels of anthocyanins (1993.02 mg/100 g), flavonoids (1026.24 mg QE/100 g), phenolic content (94.45 mg GAE/100 g), and DPPH inhibition (26.147%). Green tea and instant tea showed lower concentrations of these compounds, with instant tea consistently having the lowest values.

Proximate composition of teas prepared from papaya leaves

Table 3 presents the proximate composition of papaya leaf teas, including moisture content, ash content, protein content, and total carbohydrate content. While the overall compositions of the three tea types (black tea, green tea, and instant tea) are similar, slight variations are evident, which can be attributed to the differences in their preparation and processing methods. However, obtained result shows that moisture content ranged between 4.20% and 4.60%, with minor differences among tea types.

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Black tea showed the highest ash (8.22%) and protein content (26.17%), while carbohydrate content was relatively similar across all types, ranging from 57.02% to 58.94%, respectively.

Table 2. Bioactive compounds in papaya leave teas.

Sample	TPC (mg GAE/100 g)	TFC (mg QE/100 g)	TAC (mg/100 g)	DPPH (% inhibition)
Black tea	94.45±0.08[a]	1026.24±0.59[a]	1993.02±6.02[a]	26.14±0.01[a]
Green tea	25.26±0.06[b]	695.21±5.72[b]	908.93±1.39[b]	21.18±2.87[a]
Instant tea	6.52±0.01[c]	196.58±0.49[c]	90.55±0.80[c]	12.15±0.01[b]

*[a]: Mean±SD; Mean values with the different alphabets in the same column are significantly different at (P <0.05). **GLP**: Green leaf powder, **GLPa**: Green leaf paste, **YLP**: Yellow leaf powder, **YLPa**: Yellow leaf paste, **TPC**: Total phenolic content, **TFC**: Total flavonoid content, **TAC**: Total anthocyanin content, **DPPH**: Antioxidant activity as the amount of DPPH*

Table 3. Proximate composition of papaya leaf teas.

Sample	Moisture (%)	Ash (%)	Protein (%)	Total carbohydrate (%)
Black tea	4.55±0.07[a]	8.22±0.95	26.17±0.05	57.02±6.92
Green tea	4.60±0.05	7.27±5.21	25.17±2.82	58.94±1.39
Instant tea	4.20±0.01	7.57±0.48	25.16±0.02	57.58±0.90

[a]: Mean±SD.

Sensory evaluation of papaya leaf black teas

Table 4 presents the sensory scores for black tea prepared from papaya leaves across three brewing times (B1, B2, and B3). The color score is highest for B2 (8.26±0.03), which was brewed for 2 minutes. This indicates that a 2-minute brewing time results in the most desirable color intensity. A shorter or longer brewing time (B1 and B3) resulted in less favorable color scores. The flavor score also peaks at B2 (5.87±1.98), suggesting that the 2-minute brewing time offers the most balanced and preferred flavor. B2 again scores highest in taste (5.37±2.72), with B3 scoring the lowest (3.16±1.01). The acceptability is highest for B2 (6.74±1.29), correlating with its superior scores for color, flavor, and taste. This confirms that a balanced brew time enhances consumer preference.

Table 4. Sensory score of black tea prepared from papaya leaves.

Sample	Color	Flavor	Taste	Acceptability
B_1	6.45±0.07[b]	4.23±0.34[b]	4.87±0.15[ab]	5.02±2.20[b]
B_2	8.26±0.03[a]	5.87±1.98[a]	5.37±2.72[a]	6.74±1.29[a]
B_3	6.52±0.42[b]	3.57±0.47[c]	3.16±1.01[b]	4.58±0.13[c]

[a]: Mean±SD; Mean values with the different alphabets in the column are significantly different at (P<0.05). B_1: Black tea of 1 minute brewing time, B_2: Black tea of 2-minute brewing time, B_3: Black tea of 5-minute brewing time.

Sensory evaluation of papaya leaf green teas

Table 5 presents the sensory scores for green tea prepared from papaya leaves across three brewing times (G1, G2, and G3). G2 (brewed for 2 minutes) has the highest color score (7.96±0.13), similar to the results seen for black tea. G2 again scores the highest in flavor (6.08±0.98), suggesting that the optimal extraction of flavor compounds occurs at this brewing time. G2 leads in taste (5.37±1.32), confirming that the 2-minute brew provides the best balance of flavor and taste. G2 (7.14±1.34) receives the highest acceptability score, consistent with the trends in color, flavor, and taste. The other samples (G1 and G3) receive lower acceptability scores, likely due to their less favorable sensory attributes.

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Table 5. Sensory score of green tea prepared from papaya leaves.

Sample	Color	Flavor	Taste	Acceptability
G_1	6.55±0.11[b]	4.26±0.44[b]	4.87±0.65[ab]	5.52±2.10[b]
G_2	7.96±0.13[a]	6.08±0.98[a]	5.37±1.32[a]	7.14±1.34[a]
G_3	6.12±0.22[b]	4.11±0.87[c]	3.56±1.05[b]	4.68±0.53[c]

[a]: Mean±SD; Mean values with the different alphabets in the column are significantly different at (P<0.05). G_1: Green tea of 1 minute brewing time, G_2: Green tea of 2-minute brewing time, G_3: Green tea of 5-minute brewing time.

Sensory evaluation of papaya leaf instant tea

Table 6 presents the sensory scores for instant tea prepared from papaya leaves. Since instant tea is typically prepared by dissolving powdered leaves, there is only one set of scores available. The color score for instant tea is 7.45±1.18, which is moderate and reflects the characteristic color of tea powders. The color may not be as intense as that of freshly brewed teas due to the powdered form and processing methods. Instant tea scores 6.25±1.50 for flavor, which is reasonably high but lower than the scores for brewed black and green teas. The taste score of 6.70±0.05 for instant tea is relatively high, but not as high as the brewed versions. The acceptability score of 7.02±1.02 is relatively high, indicating that instant tea is still considered acceptable despite its slight differences from brewed teas.

Table 6. Sensory score of instant tea prepared from tea leaves.

Attributes	Sensory score
Color	7.45±1.18[a]
Flavor	6.25±1.50
Taste	6.70±0.05
Acceptability	7.02±1.02

[a]: Mean±SD.

Discussion

The findings highlight various bioactive compounds contained in papaya leaves. Green, yellow, and brown papaya leaves are rich in minerals, vitamins, and bioactive substances (Shantini *et al.*, 2021). These compounds play crucial roles in disease prevention and management, particularly in metabolic and chronic diseases. Their diverse activities include antioxidant, anti-inflammatory, and anticancer properties, making them essential for functional foods and nutraceuticals (Monika *et al.*, 2023). This study examines papaya leaves of both green and yellow varieties. An analysis of the bioactive chemicals found in green and yellow leaves, leaf powder, and paste was conducted. The DPPH free radical is a stable oxidizing agent frequently used to evaluate the antioxidant properties of various substances. According to kinetic studies, the rate at which different kinds of antioxidants react with DPPH varies; ascorbic acid has the greatest rate constant (Angeli *et al.*, 2023). The evidence indicates that green papaya leaves, especially in the powdered form (GLP), exhibited higher levels of bioactive compounds (TPC, TFC, TAC, and DPPH inhibition) compared to yellow papaya leaves and their respective paste forms. Green leaves appeared to have higher concentrations of antioxidants and polyphenolic compounds, and the GLP helped preserve these bioactive compounds better than the paste preparation. These findings align with previous studies that have highlighted the impact of processing techniques on the retention of antioxidants and bioactive compounds in plant materials Selvamuthukumaran *et al.* (Selvamuthukumaran and Shi, 2017). Phenolic compounds, particularly flavonoids and tannins, are known to contribute to the antioxidant properties of plants. The higher TPC in GLP could be due to the preservation of phenolic compounds during the drying process (Kaur and Kapoor, 2002). On the other hand, the reduction in TPC in GLPa and YLPa might be the result of phenolic compounds' degradation during the paste preparation and thermal processing Senevirathne *et al.* (Senevirathne *et al.*, 2019). The drying process

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(in GLP) is known to preserve phenolic compounds, while paste preparation (in GLPa and YLPa) may involve enzymatic degradation and heat exposure, which can reduce the phenolic content Chong *et al.* (Chong *et al.*, 2013). Flavonoids are important polyphenolic compounds that contribute to both the flavor and antioxidant properties of plants. The higher TFC in GLP suggests that the drying process may have helped retain flavonoids, which are generally heat-sensitive Nakra *et al*. (Nakra *et al.*, 2025). The lower TFC in YLPa could be due to the oxidation and thermal breakdown of flavonoids during processing. The variation in TFC among different samples could be related to the plant's age and leaf maturity, as well as the processing method. The paste preparation (in GLPa and YLPa) likely leads to some loss of flavonoid content due to enzymatic activity and heat exposure, as compared to the GLP that may better retain these compounds. The higher TAC in GLP might reflect the presence of green pigments and higher levels of anthocyanin precursors that are more stable in the powder form compared to the paste form. YLPa, having a much lower TAC, suggests that yellow papaya leaves might naturally have lower anthocyanin content, further reduced by the paste preparation Koop *et al.* (Koop *et al.*, 2022). Notably, anthocyanins are sensitive to environmental factors and processing conditions, which may explain the significant reduction in TAC in YLPa. DPPH inhibition is often used to assess the free radical scavenging ability of plant extracts, and higher levels of phenolics and flavonoids generally correlate with higher antioxidant activity Baliyan *et al*. (Baliyan *et al.*, 2022). The higher DPPH activity in GLP could be attributed to its higher phenolic and flavonoid content, both of which have been shown to contribute to antioxidant activity. The significant decrease in DPPH activity in YLPa might be a result of the combined effect of lower phenolic compounds and possible degradation during paste preparation. Therefore, the high antioxidant activity in GLP correlates with its higher TPC and TFC, while the lower DPPH inhibition in YLPa suggests a loss of these compounds due to the processing methods, particularly paste preparation.

Due to the abundance of bioactive substances and excellent antioxidant properties in green papaya leaves, three different types of tea are made from them. The superior antioxidant activity of black tea compared to green and instant teas suggests that the fermentation process used in black tea production may enhance bioactive compound extraction. Furthermore, blanching and drying methods used in green tea might have preserved more antioxidants than the spray-drying process for instant tea. Blanching is recognized to inactivate enzymes that produce browning and loss of the quality of leaves (Rudra *et al.*, 2008), as bioactive substances are easily impacted by the processing procedures (Kausilya Santhana Raja *et al.*, 2019). These findings indicate that, compared to green tea and instant tea, black tea may provide the greatest possible health advantages due to its increased antioxidant concentration and activity. These findings align with previous studies showing the impact of processing techniques on the retention of bioactive compounds in teas (Mehrabi *et al.*, 2025).

The proximate composition of papaya leaf teas shows some variation across the samples, particularly in moisture, ash, and carbohydrate content, with black tea, green tea, and instant tea exhibiting similar overall profiles. Similar findings were documented by (Maisarah *et al.*, 2014) for the desiccated papaya leaves. The differences in moisture and ash content were likely due to variations in drying conditions and processing methods, while protein and carbohydrate contents remained relatively consistent across the samples. These findings suggest that the type of processing (such as drying and powdering) does not have a major impact on the fundamental nutritional components of the tea, though slight variations are observed due to processing efficiency. These results align with similar studies on dried plant materials, where drying and processing methods played a role in nutrient retention, but differences between methods were often modest (Natumanya *et al.*, 2021).

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Colors indicate the brewed tea's visual appearance. Flavor in the context of brewed tea is the taste and scent qualities. It is subjective and can vary depending on brewing duration, tea quality, and personal tastes. Taste refers to the sensory experience of brewed tea on the taste buds, including sweetness, bitterness, astringency, etc. Like flavor, taste is a personal experience that may be impacted by the quality of the tea and the brewing conditions. The black tea brewed for 2 minutes yields the best sensory qualities in terms of color, flavor, taste, and acceptability, while longer or shorter brewing times lead to less desirable qualities. Longer brewing times result in a decrease in flavor, possibly due to over-extraction of tannins; this can contribute to bitterness (Bai *et al.*, 2023). In addition, 2-minute steep time allows for the optimal extraction of soluble compounds, while longer brewing times may lead to undesirable astringency and bitterness.

Similar to black tea, a brewing time of 2 minutes provides the best sensory qualities, particularly in terms of flavor, taste, and acceptability in green tea. A 2-minute brew optimally extracts the pigments responsible for color, providing a rich and appealing hue. Longer brewing times may lead to the extraction of excess tannins and other bitter compounds, resulting in a lower flavor score (Bai *et al.*, 2023). Over-brewing can lead to unpleasant taste qualities, possibly from excessive astringency or bitterness. Conversely, a shorter brewing time may not extract enough flavors to satisfy the panelists. A similar result was found by (Dev and Iqbal, 2015).

Instant tea has moderate sensory scores compared to freshly brewed teas, with slightly lower flavor and taste ratings but still achieves good acceptability. This suggests that while it may lack some of the nuanced sensory qualities of freshly brewed teas, it remains a convenient and acceptable alternative. Instant teas tend to have a slightly less vibrant flavor profile due to the dehydration process (Dalpathadu *et al.*, 2022). Therefore, brewing time plays a crucial role in determining the sensory qualities of both black and green teas. A 2-minute brew consistently resulted in the highest sensory scores for color, flavor, taste, and acceptability, while longer or shorter brewing times reduced the overall sensory appeal. Instant tea, although convenient, scored lower in flavor and taste compared to freshly brewed teas but still maintained a relatively high level of acceptability. The findings highlight the importance of optimizing processing conditions to improve the sensory attributes of papaya leaf teas and promote their potential for consumer acceptance.

Conclusion

In conclusion, this study highlights the potential of green papaya leaves as a valuable source for developing various types of tea, including black, green, and instant tea. The analysis of bioactive compounds and antioxidant activity shows that green papaya leaf powder contains higher levels of phenolic compounds, flavonoids, anthocyanins, and antioxidant properties than yellow papaya leaf powder. Among the tea types, black tea made from green papaya leaves demonstrated the highest concentration of these bioactive compounds and the greatest DPPH inhibition, indicating strong antioxidant potential. Sensory evaluation supports the preference for black and green teas brewed for 2 minutes, which scored highest in color, flavor, taste, and overall acceptability. These findings suggest that black tea, in particular, may provide notable health benefits due to its superior antioxidant content. Overall, the research offers promising insights into the use of papaya leaf as a functional ingredient in tea production, with both nutritional and sensory advantages. Future studies could focus on optimizing brewing parameters and evaluating the long-term health effects of consuming papaya leaf tea.

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Authors' contributions

Kauser-Ul-Alam M, Akther S, Nahid M, Quader MFB and Rahman N designed the research; Chakma S, Rahman H, Siddiqui T

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conducted the laboratory work and drafted the manuscript; Rahman N, had the primary responsibility for final content. All authors read and approved the final manuscript

Conflict of interest

There is no conflict of interest.

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