Letters in Food Research 2(2): e25080
Journal homepage: https://www.lettersinfoodresearch.com

LETTERS IN FOOD RESEARCH

RESEARCH PAPER

Total phenolic content, antioxidant activity and sensory analysis of bidara leaves (tea) infusion (*Ziziphus mauritiana*)

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Article history:
Received: 22 September 2025
Received in revised form: 24 October 2025
Accepted: 25 October 2025
Available Online: 9 November 2025

Keywords:
Herbal infusion,
DPPH scavenging activity,
Leaf maturity,
Flavonoids,
Saponins

OPEN ACCESS
Citation: Mohd Nahar, D., Nazri, F.R., Nooh, H.M. and Musa, N. (2025). Total phenolic content, antioxidant activity and sensory analysis of bidara leaves (tea) infusion (*Ziziphus mauritiana*). *Letters in Food Research*, 2(1), e25080. https://doi.org/10.26656/lfr.2.e25080

Abstract

Herbal infusions are caffeine-free beverages valued for their potential health benefits. *Ziziphus mauritiana* (Bidara) is a medicinal plant rich in flavonoids and polyphenols, traditionally recognized for its antioxidant and therapeutic properties. However, scientific studies on the nutritional and functional benefits of bidara leaves infusion are limited. This study aimed to evaluate the total phenolic content, antioxidant activity, and sensory acceptance of bidara leaf infusions prepared from different maturity stages (shoot and matured leaves) and processing methods (fresh and processed leaves) of bidara leaves. Infusions were analyzed for pH, total phenolic content (TPC), 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity, and the presence of flavonoids and saponins. Sensory evaluation was conducted to assess consumer acceptability. Results showed that the pH was influenced by leaf maturity and processing, with fresh matured leaf infusion exhibiting the highest pH (6.24). Processing methods such as drying and grinding enhanced the TPC and antioxidant activity. The TPC of processed shoot and matured leaf infusions was 18.86 mg GAE/g and 17.85 mg GAE/g, respectively, significantly higher than fresh samples. DPPH scavenging activity also increased with processing, reaching 59.65% and 60.20% in processed samples. Flavonoids and saponins were present in all samples. Sensory evaluation indicated that processed matured leaf infusion was the most preferred, scoring highest in color, mouthfeel, earthy aroma, and overall acceptability. These findings suggest that bidara leaf infusion, particularly from processed matured leaves, serves as a promising natural source of antioxidants with potential health and pharmaceutical applications.

1. Introduction

Herbal tea, also known as tisane, is a caffeine-free drink made by steeping herbs, spices, flowers, or other plant materials in hot water. These teas present a wide range of flavors, aromas, and potential health benefits. Historically, herbal drinks have been used as medicinal remedies for the elderly, drawing on ancestral wisdom. They play a significant role in the culinary traditions of various countries, including China, India, Sri Lanka, Indonesia, and Malaysia, where traditional remedies are often utilized (Shaik *et al.*, 2023). Herbal teas and beverages contain a broad spectrum of natural bioactive compounds, such as carotenoids, phenolic acids, flavonoids, coumarins, alkaloids, polyacetylenes, saponins, and terpenoids (Chandrasekara and Shahidi, 2018). There is a renewed focus on non-nutritive bioactive compounds in foods and beverages, known as "lifespan nutrients," for their potential to reduce the risk of non-communicable diseases. The growing interest in

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eISSN: 3093-7361 /
Published by Rynnye Lyan Resources

these compounds stems from their potential health benefits, even though they do not provide essential nutrients like vitamins or minerals. As part of a balanced diet, consuming herbal beverages may boost antioxidant levels and enhance overall health.

Preparing herbal infusions involves steeping herbs, spices, flowers, or other plant materials in hot water to extract their flavors, aromas, and beneficial compounds. The herbs are placed in a container, such as a teapot or mug, and hot water is poured over them. The mixture is allowed to steep for a specified time, during which the hot water extracts the desired properties from the herbs. Herbal infusions can be enjoyed hot or cold and may be sweetened or flavored to taste, offering a soothing and refreshing beverage option with potential health benefits.

Ziziphus mauritiana, commonly known as bidara, is a significant member of the Rhamnaceae family, which includes a diverse range of about 900 species across 58 genera (Jha *et al*., 2024). Native to the warm climates of Southeastern Asia, bidara has adapted to flourish in various environments, including those with salinity, drought, and waterlogging. In Malaysia, it is locally referred to as bidara, underscoring its cultural importance in the region (Jailani *et al*., 2019). With a rich history in traditional medicine, bidara has been esteemed for its therapeutic properties. Traditional practitioners have used it to treat a wide array of ailments, such as asthma, anxiety, depression, fever, inflammation, and ulcers.

Modern research has highlighted its antioxidant properties, with extracts from its fruits, leaves, and seeds showing promise in combating oxidative stress and even exhibiting potential anticancer activities. Additionally, studies have explored the hepatoprotective effects of both alcoholic and aqueous extracts of bidara leaves. These extracts have demonstrated significant pharmacological activities, suggesting broader medicinal potential beyond its traditional uses. Bidara leaves have long been valued for their medicinal properties in addressing various health conditions and bodily ailments. A study by Pambudi *et al*. (2020) indicates that the ethanol extract of bidara leaves possesses antioxidant potential, capable of counteracting the harmful effects of free radicals. According to Rialdi *et al.* (2023), bidara leaves are rich in constituents such as flavonoids, alkaloids, glycosides, saponins, resins, polyphenols, mucilage, and vitamins. Notably, flavonoids, polyphenols, and tannins are recognized for their antioxidant properties.

Numerous natural substances have played crucial roles in preserving and enhancing human health, particularly in the realm of pharmacological research where there's a keen interest in how they can influence immune responses to alleviate diseases. According to the World Health Organization (WHO), around 80% of people in developing nations rely on the use of natural compounds sourced from medicinal plants (Jha *et al*., 2024). Herbal tea infusions predominantly feature edible medicinal plants as their main components, seamlessly integrated into daily consumption routines due to its leave containing significant level of total antioxidants and total phenolics.

Traditional knowledge posits that bidara possesses medicinal properties, a belief substantiated by its extensive historical utilization in healthcare globally. Bidara leaves exhibit potential as a herbal tea, with numerous studies investigating the antioxidant capacity of bidara seeds, pulp, and peels, attributed to their rich macronutrient and phytochemical content (Rahmatallah Adenike, 2020; Jha *et al.*, 2024). However, there exists a significant research gap regarding the antioxidant activity of bidara leaves when prepared as tea (Rialdi *et al*., 2023). Furthermore, as consumer interest in natural and functional beverages continues to rise, there is an urgent need for scientific research to substantiate the health claims associated with bidara leaf tea infusion. Therefore, the objective of this study is to investigate the antioxidant properties of bidara leaf tea infusion and evaluate its sensory characteristics.

2. Material and methods

2.1 Materials

Fresh bidara leaves were collected at the backyard of Masjid Al-Ittifaqiyah, Taman Seri Gombak. The shoots of the leaves obtained at the 3^{rd} to 6^{th} row of branches from the tip of the stalk. While mature leaves obtained at the 2^{nd} to 4^{th} row of branches to the tip. The materials used for in this study, which are Whatman filter No.1, pH meter, gallic acid, Folin-Ciocalteu (0.2 N) reagent, sodium carbonate, 2,2-diphenyl-1-picrylhydrazyl radical in methanol (100%), sodium hydroxide and distilled water were obtained from Laboratory of Faculty Applied in UiTM Shah Alam.

2.2 Preparation of processed bidara leaves tea infusion

Figure 1 illustrates the preparation for both fresh and processed bidara leaves infusion. The preparation of bidara leaves tea infusion was prepared according to study conducted by Umairah Mokhtar *et al*. (2023). The bidara leaves infusion was made by using different parts of the bidara leaves which were shoots and matured leaves. The bidara leaves were washed and then dried in the tray dryer at 60°C. The dried bidara leaves then were ground into fine powder using Panasonic Mx-GM1011 grinder. Then, 1 g of the bidara leave powder inserted into tea sachet and immersed in hot distilled water for 30 minutes to make the infusion. The bidara leaves tea infusion were then filtered using Whatman paper filter No.1. Each sample was prepared in triplicate for each analysis.

2.3 Preparation of fresh bidara leaves infusion

Bidara leaves were washed and shredded then inserted into sachet and then steeped in of distilled water for 30 minutes. The bidara leaves tea infusion was then filtered using Whatman paper filter No.1 before analysis. Each sample was also prepared in triplicate for each analysis.

2.4 Determination of pH

Determination of pH of bidara leaves infusion was conducted according to Tan *et al.* (2023). infusion pH was assessed using Seveneasy pH meter, calibrated beforehand with pH 4.0, 7.0, and 9.21 standard buffer solutions. The pH reading of each sample was made in triplicate and the findings were recorded as average.

2.5 Determination of total phenolic content

The total phenolic content of the bidara leaves infusion were assessed using the Folin-Ciocalteu colorimetric method according to the study done by Umairah Mokhtar *et al*. (2023). This method involves gallic acid as the standard control. A standard solution of gallic acid ranging from 0.05 to 0.4 mg/mL was prepared to establish a calibration curve. For the assay, 1 mL of bidara leave infusion was mixed with 2.5 mL of Folin-Ciocalteu (0.2 N) reagent. Subsequently, 2 mL of sodium carbonate solution (37.7 g/L) was added and thoroughly mixed, followed by the addition of 7.5 mL of distilled water for dilution. The mixture was covered with parafilm foil and incubated in darkness for 2 hours at 30° C. The absorbance was measured at 760 nm using a UV-Visible spectrophotometer Genesys 30. The obtained results were calculated and expressed as milligrams of gallic acid equivalents (mg GAE/g) of tea infusion according to Equation 1.

$$\text{Total Phenolic Content} = cv/m \qquad \text{Equation 1}$$

Where C indicates the concentration of bidara leaves infusion in mg/mL and v indicates the volume of bidara leaves infusion while m is the weight of bidara leaves infusion. Each sample was examined in triplicate and the results were average.

2.6 Evaluation of free radical scavenging activity

The free radical (DPPH) scavenging activity of bidara leaves infusion were assets according to the Widowati *et al.* (2022) using modified DPPH (2,2-Diphenyl-1-picrylhydrazyl) assay. Afresh working solution of DPPH was prepared by dissolving 3 mg of DPPH reagent in 100 ml of methanol. This solution was covered with aluminum foil and placed in dark conditions until further use. Methanol was used as the blank. The negative control was prepared by mixing 50 µL of distilled water with 2 ml of freshly prepared DPPH solution. For the tested samples, 50 µL of bidara leaves infusions were added with 2 ml methanol. All the test tube including blank, negative control and samples were covered with aluminum foil and incubated at room temperature in the dark for 30 minutes. The absorbance of the solutions was then measured at 517 nm using a UV-Visible spectrophotometer Genesys 30. The scavenging free radical (DPPH) activity of the samples were calculated using formula:

$$\%\ \text{inhibition} = ((\text{A blank} - \text{A sample}))/((\text{A blank})) \times 100 \qquad \text{Equation 2}$$

2.7 Qualitative phytochemical analysis for flavonoid and saponin

The qualitative test for flavonoid of bidara leaves infusion was tested according to the method conducted by Umairah Mokhtar *et al*. (2023). 2 mL of bidara leaves infusion were mixed with 1 mL 2 N sodium hydroxide in a test tube. The presence of flavonoids was indicated by the presence of yellow colour, marked by a noticeable change from a colourless solution to vibrant yellow colour. The presence of saponin for bidara leaves infusion were also tested according to method conducted by Umairah Mokhtar *et al*. (2023). For the saponin test, 2 mL of bidara leaves infusion were mixed with 6 mL of distilled water in a test tube. The mixture was vigorously shaken until the presence of 2 cm foam can be observed.

2.8 Sensory evaluation

In this study, the sensory evaluation of bidara leaves tea infusion was conducted to determine the acceptability of bidara leaves tea infusion and leaves of different maturity stages and processing method in terms of colour, bitterness, astringency, mouthfeel, earthy, aftertaste, and overall acceptability. The sensory evaluation bidara leaves infusion involve 30 panelists, in which the panelists were required to evaluate the bidara leaves tea using 9-point hedonic scale, where 1 indicates dislike extremely and 9 indicates like extremely. The scores rated by the panelists were recorded and calculated to determine the significance difference using ANOVA.

2.9 Statistical analysis

The values were expressed as the mean ± standard deviation of three replicates. Statistical comparison between the means was conducted using ANOVA by and followed by Tukey's multiple comparison test. A significance level of $P < 0.05$ was considered significant for all statistical tests. All analyses were conducted using SPSS software (version 17).

https://doi.org/10.26656/lfr.2.e25080

Table 1. pH of bidara leaves infusion.

Sample	pH
Fresh shoot	5.93 ± 0.05[c]
Fresh matured	6.24 ± 0.10[a]
Processed shoot	5.91 ± 0.01[c]
Processed matured	6.18 ± 0.01[b]

3. Results and discussion

3.1 pH

The pH of the bidara leaves infusion for all samples are shown in Table 1. According to Table 1, the pH levels of bidara infusions vary depending on the maturity of the leaves and their processing state. A study conducted by Tan *et al*. (2023) found that the pH of green tea infusion was between 5.10 to 6.10. Remarkably, the pH of the samples aligns with the study. For shoots samples, there was no significance different between processed shoot and fresh shoot. In contrast, mature leaves produce infusions with fresh mature leaves create an infusion with a pH of 6.24, whereas processed mature leaves yield a slightly more acidic infusion with a pH of 6.18.

The maturity of bidara leaves plays a significant role in their chemical composition, which directly affects the acidity of the infusion. Shoot leaves tissues often have high levels of nutrients to support rapid growth and development, leading to a greater accumulation of organic acids compared to their matured counterparts (Wiggins *et al*., 2016; Rao *et al*., 2021). These organic acids lower the pH of the leaves thus; the pH of matured leaves is higher than shoot leaves. As matured leaves undergo rapid photosynthesis and cell division, they tend to have higher level of basic compounds such as amino acid and organic bases that elevates the pH of the leaves (Bielczynski *et al*., 2017).

Furthermore, different preparation technique such as drying and grinding can alter the solubility and availability of acidic compounds in the infusion. Table 1 illustrates that the pH of bidara infusion of fresh matured leaves is higher than the processed matured leaves. This is due to fresh leaves has higher water content that dilute the concentration of acidic compound. Moreover, fresh leaves contain organic acids such as and phenolic compound, and bioactive as in their native form, in which they are not altered by enzymatic degradation. A study conducted by Mahanom *et al*. (1999) reveals that chlorophyll II in fresh leaves is higher than in dried leaves. Chlorophyll is more abundant in fresh leaves and has a stabilizing effect on the pH due to its mild alkaline nature. These compound acts as buffer and maintaining the pH of the infusion (Aaqil *et al*., 2023). In contrast to process leaves, drying process causes can lead to significant degradation of chlorophyll and other compound and lead to the infusion become more acidic.

3.2 Total phenolic content

Total phenolic content measures the total of concentration of phenolic compound presents in the sample. Phenolic compound includes flavonoids, phenolic acids, tannins and stilbenes. The total phenolic content of bidara leaves infusion were determine using Folin-Ciocalteu assay where it involves the reduction of phosphomolybdate-phosphotungstate complex of phenolic by antioxidant in alkaline solution, producing a blue colour whose intensity is measured spectrophotometrically at 760 nm (Pérez *et al*., 2023). Gallic acid standards with concentrations ranging from 0.05 to 0.4 mg/ml (specifically 0.05, 0.12, 0.19, 0.26, 0.33, and 0.4 mg/ml) were employed to quantify the total phenolic content in the infusion of bidara leaves. Table 2 shows the total phenolic content of the bidara leaves infusion. A standard curve of absorbance versus concentration yielded the equation $y = 5.3362x - 0.251$ with a correlation coefficient $r^2 = 0.9924$, indicating excellent linearity. This equation was used to calculate the total phenolic content of the samples, expressed as mg GAE/g.

The total phenolic content (TPC) of plant leaves can vary significantly between fresh and processed samples. Processing generally leads to a substantial increase in total phenolic content. As shown in Table 2, total phenolic content of both processed shoots and processed matured leaves infusion were 18.86 mg GAE/g and 17.85 mg GAE/g, in which, it is significantly higher than fresh shoots and fresh mature leaves infusion ($P<0.05$). This significant difference suggests that processing methods, such as drying and grinding, may enhance the extraction or availability of phenolic compounds. A study total phenolic content of tamarind leaves conducted by Jimenez-Garcia *et al*. (2020) also shows increasing trend between fresh tamarind leaves and processed tamarind leaves. Drying breaks down the cell wall structure and facilitates water removal and enhancing the release of intracellular compounds such as polyphenols by making them more accessible for extraction (Jimenez-Garcia *et al*., 2020). According to Ngamsuk *et al.* (2019), the high total phenolic content in dried samples may result from an increase in bound phenolic compounds, which occurs due to the breakdown of cellular structures during the drying process. This structural degradation facilitates the release of phenolics and makes them more accessible for extraction. Phenolic compound may release into the solvent as a result of cell wall collapse cell wall during the drying process. The release of large number of bound phytochemicals into the medium called phenolic compound from the matrix, thus making them more accessible for extraction by solvent (Ngamsuk *et al*., 2019).

Difference in total phenolic content observed between processed shoot and mature leaves infusion can be linked to their cell wall structure and its main component, called cellulose and effect of drying on this tissue. Cellulose is the main cell wall component that compose of linear chain of β-1,4 linked d-glucose units, forms microfibrils that aggregate into larger microfibrils. These structures lend the cell wall its incredible strength, rivalling the tensile strength of steel (Baez and Bacete, 2023). A study conducted by Kern *et al.* (2022) reveals that the lowest alpha-cellulose yields observed in arboreal species was noted for young leaves, representing the leaf expansion phase. As the leaves developed, the alpha-cellulose content simultaneously increase, providing the necessary structural support for the matured leaves making them to have more robust cell walls that retain bound phenolics even after drying compared to shoot leave. In contrast, young shoot leaves with lower alpha-cellulose content have thinner and less rigid cell walls, making them to more prone to collapse during drying that facilitates the release of bound phenolics into the extraction solvent.

As for fresh leaves infusion, there was also notable significant difference between fresh shoot infusion and fresh matured infusion. According to Table 2, fresh matured leaves infusion has significantly higher total phenolic content than fresh shoot leaves infusion. This is because mature leaves typically have a longer growth period, allowing them to accumulate higher level of phenolic compounds. A study conducted by Batubara *et al.* (2020) reveals that mature leaves also have the optimum ability to produce secondary metabolites that leading to higher level of phenolic content than shoots leaves.

3.3 Free radical (DPPH) scavenging activity

The DPPH free radical scavenging activity reveals significant differences in antioxidant capacity across the different sample types. As shown in Table 2, fresh shoots exhibited moderate antioxidant activity 16.73%, which was significantly higher than 3.26% that of fresh matured shoots This suggests that younger shoots contain more potent antioxidant compounds, potentially due to higher levels of phenolic compounds or other bioactive molecules associated with rapid growth and development. In contrast, processed samples showed markedly enhanced scavenging activity, with processed shoots 59.56% and processed matured shoots 60.20% both demonstrating significantly higher values compared to their fresh counterparts. Interestingly, the difference between processed shoots and processed matured shoots was minimal, indicating that processing plays a more critical role in enhancing antioxidant activity than the developmental stage of the sample.

Drying eliminates moisture from the leaves, thereby concentrating the phenolic compounds present. Fresh leaves, which contain a substantial amount of water, have a diluted concentration of these beneficial compounds. As the leaves dry and moisture decreases, the concentration of phenolics per gram of leaf material increases. This concentration effect leads to processed tea having a higher total phenolic content (Jimenez-Garcia *et al*., 2020). Moreover, the higher TPC in processed leaves could be attributed to the breakdown of cellular structures, facilitating better extraction of phenolic compounds, or to chemical changes during processing that convert bound phenolics into more readily extractable forms grinding process also will increases the surface area of the dried leaves, facilitating better extraction of phenolic compounds during brewing. Smaller particle sizes allow for more efficient solvent penetration when hot water is added, leading to improved extraction rates of soluble phenolics. Studies indicated that finely ground materials can yield significantly higher amounts of bioactive compounds compared to whole or coarsely ground materials due to enhanced accessibility during extraction processes (Rialdi *et al*., 2023.). Processing method such as drying and grinding can also stabilize certain phenolic compounds that may degrade or change in structure when fresh. For example, some phenolics may undergo transformations that enhance their antioxidant properties during drying and grinding. In contrast, fresh leaves may contain more unstable compounds that do not contribute as effectively to total phenolic content in infusions. This can be supported by research done by Akther *et al.* (2024) where it has been noted that the total phenolic content in powdered samples was higher than in fresh mango, suggesting that drying methods are effective in preserving total phenolic content (TPC) during powder production.

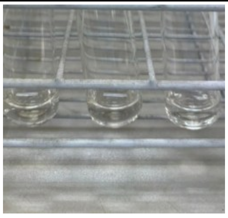
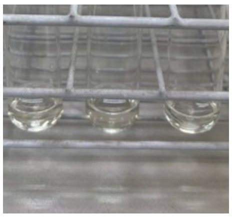
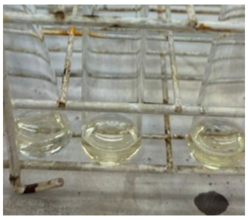
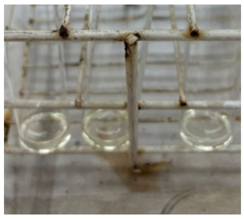
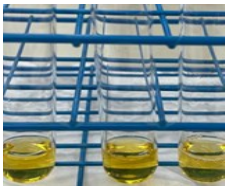
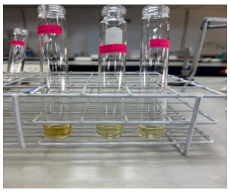
Mature leaves generally contain slightly higher phenolic content than shoot leaves in their fresh state, possibly due to the accumulation of these compounds as the leaves age. As bidara leaves mature, they accumulate higher concentrations of secondary metabolites, including phenolic compounds. These compounds serve various functions in plants, and their levels tend to increase with leaf maturity. Mature leaves often contain more flavonoids, tannins, and other phenolic compounds, which contribute to a higher TPC compared to younger

Table 2. Total phenolic content (mg GAE/g) and scavenging activity (%) of bidara leaves infusion.

	Fresh shoot	Fresh matured	Processed shoot	Processed matured
Total phenolic content (mg GAE/g)	3.18 ± 0.09^{d}	3.02 ± 0.02^{c}	18.86 ± 0.02^{a}	17.05 ± 0.03^{b}
Free radical scavenging activity (%)	16.73 ± 0.36^{b}	11.82 ± 0.34^{c}	59.56 ± 0.27^{a}	60.20 ± 0.30^{a}

https://doi.org/10.26656/lfr.2.e25080

Table 3. Observation on the presence of flavonoid in bidara leaves infusion.

	Fresh shoot	Fresh matured	Processed shoot	Processed matured
Before				
After				

leaves that may not have fully developed these compounds (Batubara *et al*., 2020).

3.4 Qualitative phytochemical analysis for flavonoid and saponin

The presence of flavonoids in bidara leaf infusion was indicated by a yellow color after adding 1 ml of 2N sodium hydroxide, observed in all samples. As shown in Table 3, all of the samples changed into yellow colour after the addition of sodium hydroxide. Meanwhile, Saponin presence was confirmed by foam formation after vigorous shaking, also seen in Table 4, where all the samples formed foam. These tests indicate that bidara leaves contain both flavonoids and saponins, which are essential bioactive compounds known for their various health benefits.

Flavonoids are a group of polyphenolic compounds that possess antioxidant, anti-inflammatory, and antimicrobial properties, which contribute to improving immune function, reducing oxidative stress, and potentially preventing chronic diseases (Ullah *et al*., 2020). Saponins, on the other hand, are glycosides with soap-like properties that are known to have immune-boosting effects, cholesterol-lowering abilities, and potential anti-cancer properties (Mugford and Osbourn, 2012). Together, these compounds make bidara leaves a valuable source of natural bioactive substances, offering numerous therapeutic potentials for health promotion and disease prevention. Flavonoids possess antioxidant properties, and saponins contribute to various biological activities. The presence of these compounds in all samples suggests that bidara leaves retain these beneficial phytochemicals regardless of maturity or processing, although quantitative differences may exist as processing methods such as drying and grinding can significantly enhance the extraction efficiency of flavonoids and saponins. For example, dried and ground bidara leaves often yield higher concentrations of these compounds because the removal of moisture concentrates the bioactive substances, while grinding increases surface area, facilitating better solvent penetration during extraction.

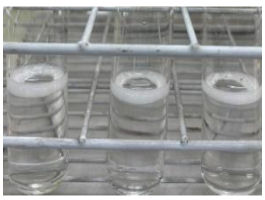
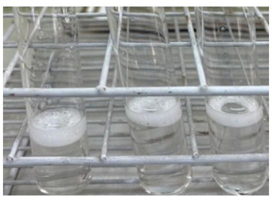
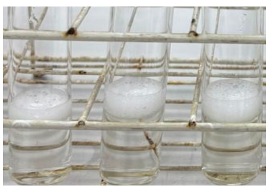
3.5 Sensory evaluation

The sensory evaluation of bidara leaves infusions highlights distinct differences in sensory attributes across the four sample types (fresh shoot, fresh matured, processed shoot, and processed matured). For colour, processed samples were rated significantly higher, with processed matured scoring the highest 6.68 compared to processed shoot 6.18, while fresh samples had much lower scores, with fresh matured 3.68 slightly trailing fresh shoot 3.77. This indicates that processing enhances the visual appeal, likely through intensified color development during drying or other treatments.

Bitterness was most pronounced in fresh shoot samples 5.47, whereas processed shoot had the lowest bitterness score 4.32. This suggests that processing reduces the perception of bitterness, potentially due to chemical changes that mask or modify bitter compounds. Similarly, astringency was moderate across all samples, with processed matured scoring slightly higher 5.00 compared to fresh matured 4.32 and fresh shoot 4.79.

Mouthfeel scores were highest for processed matured (5.18) indicating that this sample was perceived

Table 4. Observation on the presence of saponin in bidara leaves infusion.

Fresh shoot	Fresh matured	Processed shoot	Processed matured
			

https://doi.org/10.26656/lfr.2.e25080

Table 5. Mean score of 9-point hedonic scale of bidara leaves infusion.

	Fresh shoot	Fresh matured	Processed shoot	Processed matured
Colour	3.77[b]	3.68[b]	6.18[a]	6.68[a]
Bitterness	5.47[a]	4.35[b]	4.32[b]	5.09[ab]
Astringency	4.79[a]	4.32[a]	4.44[a]	5.00[a]
Mouthfeel	5.09[a]	4.00[a]	4.68[ab]	5.18[a]
Earthy	5.12[ab]	4.27[b]	4.85[ab]	5.68[a]
Aftertaste	5.21[a]	4.41[a]	4.41[a]	5.03[a]
Overall acceptability	5.09[ab]	4.41[b]	4.82[ab]	5.29[a]

as having the most desirable texture. Fresh samples, particularly fresh matured (4.000), had lower mouthfeel scores, suggesting less favorable tactile sensations. Earthy flavor followed a similar trend, with processed matured (5.68) rated higher than other samples, reflecting an enhancement of desirable earthy notes during processing.

Aftertaste scores showed minimal variation but processed matured 5.03. was rated slightly higher than other samples, indicating a more pleasant lingering flavor. Overall acceptability was highest for processed matured 5.29 and lowest for fresh matured 4.41, reinforcing the observation that processing improves the sensory appeal of bidara leaves infusions (Table 5). These results suggest that processing enhances various sensory qualities, particularly colour, mouthfeel, and overall acceptability, making processed matured leaves the most preferred choice among the samples.

Conclusions

This study highlights the potential of *Ziziphus mauritiana* (Bidara) leaves as a promising herbal infusion with significant antioxidant and health-enhancing properties. The findings demonstrate that both leaf maturity and processing methods influence the physicochemical, phytochemical, and sensory attributes of the infusion. Processing, particularly drying and grinding, improves the extraction and stability of bioactive compounds while enhancing sensory qualities such as color, aroma, and overall acceptability. The consistent presence of flavonoids and saponins underscores bidara's role as a natural source of antioxidants and therapeutic compounds capable of mitigating oxidative stress and supporting overall well-being. The research affirms the infusion's value as a caffeine-free, functional beverage with potential applications in nutraceutical and pharmaceutical development.

Conflict of interests

The authors affirm that they have no competing financial interests or personal connections that could be perceived as having impacted the work described in this article.

Acknowledgements

The researchers express their heartfelt gratitude to the Faculty of Applied Science, Universiti Teknologi MARA Shah Alam, Malaysia. The study was supported by Faculty of Applied Sciences, Universiti Teknologi MARA, Shah Alam Selangor, Malaysia.

Declaration of generative AI in the scientific writing process

During the preparation of this work, the author(s) used ChatGPT to improve language clarity and structure. The author(s) have reviewed and edited the content as needed. The authors will take full responsibility for the content of the published article.

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