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RESEARCH ARTICLE

FORMULATION AND QUALITY DETERMINATION OF HERBAL CARBONATED SODA ENRICHED WITH CORIANDER, TAMARIND AND GREEN APPLE AS NATURAL BASE INGREDIENTS

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ABSTRACT

Herbal-inspired beverages represent a promising avenue for developing functional, naturally flavored carbonated drinks. This study aimed to formulate and characterize three soda formulations based on coriander (*Coriandrum sativum*), tamarind (*Tamarindus indica*), and green apple (*Malus domestica*), enriched with commercially available ingredients such as dried barley seeds (*Hordeum vulgare* L.), dried ginger (*Zingiber officinale*), fresh beetroot (*Beta vulgaris*) (for coriander formulation), dried ashwagandha (*Withania somnifera*) roots (tamarind formulation) and dried tulsi (*Ocimum tenuiflorum*) leaves (for green apple formulation). Each formulation was evaluated under three sweetening systems: bee honey, stevia, and a sugar–stevia blend to identify the most acceptable sensory profile (9-point hedonic scale, n=35). Sensory analysis indicated that the sugar–stevia blend consistently achieved the highest overall acceptability across all formulations, with mean ranks of 2.23 (coriander), 2.93 (tamarind), and 2.43 (green apple). Physicochemical evaluation revealed that the formulated sodas exhibited higher pH values (4.76, 2.70, 3.01) compared with a commercial cola (2.63), lower total soluble solids (4.29 – 6.04 °Brix vs 10.08 °Brix), reduced total and reducing sugars (2.27 – 9.02 g/100 mL vs 10.51 g/100 mL), and markedly lower sodium content (1.50 – 8.31 mg/L vs 51.23 mg/L). Carbonation levels were lower (1.08–1.14 volumes CO_2) relative to cola (3.74 volumes CO_2). Functional analysis demonstrated enhanced bioactive properties, with ascorbic acid concentrations ranging from 6.28 to 20.99 mg/100 mL, total phenolic content of 192 – 374 mg GAE/L, and DPPH radical-scavenging activity up to 58.58% in coriander soda. Total plate count analysis confirmed microbiological stability during 14 days of refrigerated storage, with no significant increase ($p > 0.05$) in microbial counts, which ranged from 730 – 1000 CFU/mL at baseline to 590 – 600 CFU/mL after storage. The pH of all soda formulations increased during storage (from 2.70 – 4.76 to 2.86 – 4.89), with greater increases observed at elevated storage temperatures (25 and 40°C) than under refrigerated conditions (4°C). These findings indicate that herbal carbonated sodas can deliver a nutritionally enriched, low-sugar (total and reducing sugar), and sensory-acceptable alternative to conventional soft drinks.

Keywords: Antioxidant Activity; Bioactive potential; Carbonation; Phenolics; Sensory Acceptability

INTRODUCTION

Carbonated soft drinks (CSDs) remain among the most widely consumed beverages worldwide and continue to contribute substantially to daily energy and free sugar intake across many populations. In the United States, approximately half of the adults consume sugar-sweetened beverages (SSBs), including regular sodas, on any given day, reflecting the continued dietary relevance of these products despite increasing public health concerns (Lee *et al*., 2023; Zagorsky and Smith, 2020). Similarly, in Australia, soda is one of the most commonly consumed SSB categories and a major contributor to sugar intake among adolescents, particularly males, who are among the highest consumers (Miller *et al*., 2020). Conventional soft drinks are typically energy-dense, high in added sugars, and low in micronutrient content, resulting in a poor nutrient-to-energy ratio and an

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increased risk of excessive caloric intake (Rusmevichientong *et al*., 2018). These consumption patterns have intensified concerns regarding the contribution of sweetened carbonated beverages to diet-related non-communicable diseases such as Type 2 diabetes, obesity and cardiovascular disease.

The health consequences of habitual soda consumption extend beyond excess calorie intake. Epidemiological and meta-analytic evidence consistently links regular consumption of sugar-sweetened sodas with adverse metabolic and chronic disease outcomes. Yu *et al*. (2023) reported significant positive associations between consumption of sugar-sweetened and artificially sweetened soda and obesity. Similarly, Sun *et al*. (2023) demonstrated a statistically significant association between sugar-sweetened soda intake and non-alcoholic fatty liver disease. Additional systematic reviews and meta-analyses have shown that sugar-sweetened soda consumption is associated with increased risk of chronic kidney disease (Cheungpasitporn *et al*., 2014), while both sugar-sweetened and artificially sweetened soda consumption have been linked to hypertension (Cheungpasitporn *et al*., 2015). Collectively, these findings reinforce the public health need to reduce dependence on conventional sodas and to develop nutritionally improved alternatives that remain appealing to consumers.

The mechanisms underlying these associations are multifactorial. Fructose, a major constituent of many sugar-sweetened beverages, is predominantly metabolized in the liver and can promote de novo lipogenesis, hepatic fat accumulation, insulin resistance, and visceral adiposity, thereby contributing to the development of obesity and non-alcoholic fatty liver disease (Malik & Hu, 2022). High levels of rapidly absorbable sugars may promote positive energy balance, insulin resistance, impaired glycaemic regulation, and adiposity (Yu *et al*., 2023). In addition, many soft drinks are highly acidic, often with pH values below 3, which may contribute to enamel erosion, gastrointestinal irritation, and alterations in gut microbial ecology, thereby potentially exacerbating metabolic disturbances (Diaz *et al*., 2023). Public health strategies such as warning labels, taxation, and mass media campaigns increasingly target SSB reduction; however, consumer responses remain mixed. Although many consumers perceive soda, diet soda, and energy drinks as unhealthy options, frequent SSB consumers may still be more likely to perceive these beverages as relatively acceptable or healthy, complicating behaviour -change interventions (Miller *et al*., 2022). Moreover, reduced SSB intake may not always lead to healthier beverage choices, as consumers may substitute with artificially sweetened beverages rather than water or more nutritious alternatives (Teng *et al*., 2019).

Concurrently, the global beverage industry is shifting towards clean-label, natural, organic, and minimally processed products (Asioli *et al*., 2017). Consumers increasingly seek beverages that provide refreshment while aligning with health-conscious preferences, ingredient transparency, and reduced use of synthetic additives. In this context, functional carbonated beverages represent an emerging area of scientific and commercial interest. Traditional and ethnobotanical beverage systems have long incorporated herbs, spices, and plant extracts for both refreshment and therapeutic purposes. These ingredients are rich in bioactive phytochemicals, including polyphenols, flavonoids, organic acids, and vitamins, which may offer antioxidant, anti-inflammatory, antimicrobial, digestive, and adaptogenic benefits (Shaik *et al*., 2023). However, despite this potential, the integration of herbal ingredients into carbonated beverage systems remains underexplored, particularly with respect to formulation, physicochemical stability, sensory acceptability, and functional characterization.

The development of herbal carbonated sodas offers a promising pathway for innovation within this space. Ayurvedic food traditions emphasize botanicals for both flavor and physiological balance (Payyappallimana and Venkatasubramanian, 2016). Yet few studies have examined carbonated beverages that successfully combine such ingredients into formulations that are both sensory-acceptable and functionally meaningful (Aamir *et al.*, 2024; Cedeño Barre & Gorozabel Muñoz, 2021). This is particularly relevant because carbonation, acidity, sweetness balance, colour stability, and flavour interactions can significantly influence both consumer acceptance and the retention of bioactive properties. Therefore, the present study aimed to formulate and characterise a range of herbal carbonated sodas using commercially available coriander seeds, tamarind pulp, and green apple, and to enrich them with barley seeds, dried ginger, fresh beetroot, dried tulsi leaves, and dried ashwagandha roots. This study evaluates the feasibility of developing a clean-label, naturally flavoured carbonated beverage as a healthier alternative to conventional sodas while maintaining desirable physicochemical, sensory, and functional properties.

MATERIALS AND METHODS

This study was conducted at the Department of Food Science and Technology, Faculty of Agriculture, University of Peradeniya, Sri Lanka. The plant materials used for beverage formulation were commercially available coriander seeds (*Coriandrum sativum*), dried barley seeds (*Hordeum vulgare* L.), dried ginger rhizomes (*Zingiber officinale*), fresh beetroot (*Beta vulgaris*), dried tulsi leaves (*Ocimum tenuiflorum*), fresh green apples (*Malus domestica*), dried tamarind pods (*Tamarindus indica*), and dried ashwagandha roots (*Withania somnifera*). Bee honey, stevia powder, and a sugar–stevia blend were used as sweetening agents during formulation screening.

Analytical-grade reagents that were obtained from the laboratory stocks of the Department of Food Science and Technology, University of Peradeniya were used throughout the study, including hydrochloric acid (HCl), sodium hydroxide (NaOH), phenolphthalein, methylene blue, chloroform, methanol, sodium chloride (NaCl), sodium sulfate (Na_2SO_4), sulfuric acid (H_2SO_4), copper sulfate ($CuSO_4$), potassium sulfate (K_2SO_4), boric acid, bromocresol green, 2,2-diphenyl-1-picrylhydrazyl (DPPH), Folin–Ciocalteu reagent, gallic acid, sodium carbonate (Na_2CO_3), metaphosphoric acid, and 2,6-dichlorophenolindophenol (DCPIP).

Major equipment included a digital pH meter (SensionTM$^+$ PH3, Hach Company, Loveland, CO, USA), digital refractometer (PAL-3 Pocket Refractometer, ATAGO Co., Tokyo, Japan), carbonation machine (LS-MCS, Zhangjiagang Hao Pak Machinary Co., Zhangjiagang, Jiangsu, China), CO_2 tester (Series 1000 SS-60, Zahm & Nagel Co., Holland, OH, USA), UV–visible spectrophotometer (AE-S90-MD, A&E Lab Instruments, China), flame photometer (Jenway model PFP7, Cole-Parmer Ltd., Staffordshire, UK), centrifuge (Himac CT 4D, Hitachi Koki Co., Tokyo, Japan), Kjeldahl digestion and distillation units (VELP Scientifica, Usmate Velate, Italy), incubator (IC 600, Memmert GmbH + Co. KG, Schwabach, Germany), drying oven (Isotemp 200 Series, Thermo Fisher Scientific, Waltham, MA, USA), and autoclave (HICLAVE HV-50, Hirayama Manufacturing Corporation, Saitama, Japan).

Experimental design and formulation development

Three herbal carbonated soda formulations were developed through preliminary trial-based optimization based on ingredient compatibility, flavor balance, and process feasibility. The formulations consisted of a coriander-based soda (F1), a tamarind-based soda (F2) and a green apple-based soda (F3). Each formulation was prepared with three sweetening treatments: T1 (bee honey), T2 (stevia powder), and T3 (sugar–stevia blend), yielding a total of nine treatment combinations (F1T1– F3T3). The experiment was conducted using a completely randomized design (CRD), and each treatment was prepared in triplicate. Sensory evaluation was conducted separately for each formulation to determine the most acceptable sweetening system. A panel of 35 untrained consumers evaluated the samples using a 9-point hedonic scale ranging from 1 (“dislike extremely”) to 9 (“like extremely”). Appearance, aroma, taste, mouthfeel, and overall acceptability were assessed. The sweetening treatment receiving the highest mean overall acceptability score within each formulation was selected for subsequent product preparation and physicochemical and nutritional analyses. A commercial cola beverage was included as an external reference control for comparative assessment. The preliminary formulations and sweetening treatments used during formulation screening are summarized in Table 1.

Extraction, carbonation, and packaging

Table 1. Formulation matrix and sweetening treatments used for the development and sensory screening of herbal carbonated sodas

FC	PD	PBI	CI	IL (g/L)	STC	SS	SL/R
F1–T1	Coriander-based functional soda	Coriander seed (*Coriandrum sativum*)	Ginger (*Zingiber officinale*); Beetroot (*Beta vulgaris*); Barley (*Hordeum vulgare*)	Coriander = [16.6]; Ginger = [50]; Beetroot = [33.3]; Barley = [50]	T1	Bee honey	[10] g/L or [1] % (w/v)
F1–T2	Coriander-based functional soda	Coriander seed (*Coriandrum sativum*)	Ginger (*Zingiber officinale*); Beetroot (*Beta vulgaris*); Barley (*Hordeum vulgare*)	Coriander = [16.6]; Ginger = [50]; Beetroot = [33.3]; Barley = [50]	T2	Stevia powder	[1] g/L or [0.1] % (w/v)
F1–T3	Coriander-based functional soda	Coriander seed (*Coriandrum sativum*)	Ginger (*Zingiber officinale*); Beetroot (*Beta vulgaris*); Barley (*Hordeum vulgare*)	Coriander = [16.6]; Ginger = [50]; Beetroot = [33.3]; Barley = [50]	T3	Sugar–stevia blend	Sugar = [22] g/L + Stevia = [0.5] g/L **or** [44]: [1] ratio
F2–T1	Tamarind-based functional soda	Tamarind (*Tamarindus indica*)	Ashwagandha root (*Withania somnifera*)	Tamarind = [58.3]; Ashwagandha = [5.8]	T1	Bee honey	[10] g/L or [1] % (w/v)
F2–T2	Tamarind-based functional soda	Tamarind (*Tamarindus indica*)	Ashwagandha root (*Withania somnifera*)	Tamarind = [58.3]; Ashwagandha = [5.8]	T2	Stevia powder	[1.5] g/L or [0.15] % (w/v)
F2–T3	Tamarind-based functional soda	Tamarind (*Tamarindus indica*)	Ashwagandha root (*Withania somnifera*)	Tamarind = [58.3]; Ashwagandha = [5.8]	T3	Sugar–stevia blend	Sugar = [50] g/L + Stevia = [1] g/L **or** [50]: [1] ratio
F3–T1	Green apple-based functional soda	Green apple (*Malus domestica*)	Tulsi leaves (*Ocimum tenuiflorum*)	Green apple = [85.1]; Tulsi = [8.4]	T1	Bee honey	[15] g/L or [1.5] % (w/v)
F3–T2	Green apple-based functional soda	Green apple (*Malus domestica*)	Tulsi leaves (*Ocimum tenuiflorum*)	Green apple = [85.1]; Tulsi = [8.4]	T2	Stevia powder	[1.5] g/L or [0.15] % (w/v)
F3–T3	Green apple-based functional soda	Green apple (*Malus domestica*)	Tulsi leaves (*Ocimum tenuiflorum*)	Green apple = [85.1]; Tulsi = [8.4]	T3	Sugar–stevia blend	Sugar = [50] g/L + Stevia = [1] g/L **or** [50]: [1] ratio
C	Commercial cola beverage (reference control)	Commercially available cola beverage	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable

FC: Formulation code, PD: Product description, PBI: Primary base ingredient(s), CI: Complementary ingredient(s), IL: Ingredient level, STC: Sweetening treatment code, SS: Sweetener system and SL/R: Sweetener level/ratio
Note: F1 = coriander-based functional soda; F2 = tamarind-based functional soda; F3 = green apple-based functional soda. T1 = bee honey; T2 = stevia powder; T3 = sugar–stevia blend. The formulation screening experiment consisted of a 3 × 3 combination of formulation type and sweetening treatment, resulting in nine treatment combinations. Ingredient levels are expressed as grams per litre (g/L) of beverage formulation. The incorporation of the sweetening agent for each formulation was determined through a trial-and-error procedure. The commercial cola beverage (C) was included only as a reference control for comparative physicochemical, nutritional, and functional evaluation and was not included in the sensory screening experiment

Based on the sensory screening study, the most preferred sweetening treatment for each formulation was selected for further product preparation and characterization. The selected formulations were F1 (coriander-based soda), F2 (tamarind-based soda), and F3 (green apple-based soda). For each selected formulation, water was heated to approximately 60 ^{o}C and the respective sweetening agent was dissolved. The botanical ingredients were then added to a strainer and infused in water. Specifically, F1 contained coriander seeds, dried ginger, beetroot, and barley; F2 contained tamarind pulp and dried ashwagandha roots; and F3 contained fresh green apple pieces and dried tulsi leaves. The infusion was maintained at approximately 80 ^{o}C for 10 min, after which the extract was filtered and cooled to 4 ^{o}C before carbonation to enhance carbon dioxide solubility. Carbonation was carried out using a manual carbonation machine (LS-MCS, Zhangjiagang Hao Pak Machinery Co., Zhangjiagang, Jiangsu, China) according to the manufacturer's instructions (pressure of 0.15 MPa and temperature of 4 ^{o}C). The carbonated beverages were immediately filled into two-piece aluminium cans and hermetically sealed. The final products were subsequently subjected to physicochemical, bioactive, and storage stability analyses. Unless otherwise stated, all analyses were performed using degassed samples to avoid analytical interference from dissolved carbon dioxide.

Physicochemical characterization

pH

The pH of each formulation was measured using a digital pH meter (SensionTM+ PH3, Hach Company, Loveland, CO, USA) calibrated with standard buffer solutions (pH 4.01, 7.00, and 9.80). Approximately 5 mL of each degassed sample was used for measurement, and the mean value was reported.

Total soluble solids

Total soluble solids were measured using a digital refractometer (PAL-3 Pocket Refractometer, ATAGO Co., Tokyo, Japan) calibrated with distilled water and expressed as ^{o}Brix.

Total sugar content

Total sugar content was determined using the Lane and Eynon titrimetric method after acid inversion of sucrose (Sewwandi *et al*., 2020). Briefly, a weighed portion of each degassed sample was diluted with distilled water, hydrolysed with concentrated HCl by boiling, neutralized with NaOH, and made up to volume. The hydrolysed sample was titrated against Fehling's A and B solutions using methylene blue as the internal indicator. Results were expressed as g/100 mL.

Reducing sugar content

The reducing sugar content was determined using the Lane and Eynon method, as described by Sewwandi *et al*. (2020). Diluted degassed samples were titrated directly against Fehling's A and B solutions with methylene blue as the endpoint indicator. Results were expressed as g/100 mL.

Titratable acidity

Titratable acidity was determined according to Paul *et al*. (2010). Degassed samples were diluted, and aliquots were titrated against 0.01 N NaOH using phenolphthalein as the indicator until a pale pink endpoint was obtained. Results were expressed as % titratable acidity.

Crude fat

Crude fat content was determined using the Folch extraction method (Axelsson and Gentili, 2014). Samples were extracted using chloroform: methanol (2:1, v/v), followed by phase separation with 0.9% NaCl. The chloroform phase was collected, dried over sodium sulfate, evaporated, and the residue was gravimetrically quantified. Results were expressed as % (w/w).

Crude protein

Crude protein was determined by the Kjeldahl method (Aguirre, 2023). Samples were digested with concentrated sulfuric acid in the presence of $CuSO_4$ and K_2SO_4, followed by distillation into boric acid and titration with standardized HCl. Nitrogen content was converted to protein using a factor of 6.25. Three independent sample replicates were analyzed, and each sample was measured in duplicate. Results were expressed as % (w/w).

Sodium content

Sodium concentration was measured using flame photometry (Jenway model PFP7, Cole -Parmer Ltd., Staffordshire, UK). A sodium standard curve (0–50 mg/L) was prepared, and filtered, degassed samples were directly aspirated into the instrument. Results were expressed as mg/L.

Carbonation level

Carbonation level was determined using a Zahm and Nagel CO_2 tester (Series 1000 SS-60, Zahm & Nagel Co., Holland, OH, USA) by measuring internal can pressure and sample temperature. Dissolved CO_2 was estimated from the standard carbonation chart and expressed as volumes of CO_2.

Determination of bioactive compounds

For bioactive compound analysis, methanolic extracts of degassed soda samples were prepared by mixing the sample with absolute methanol, shaking for 3 h, and centrifuging (Himac CT 4D, Hitachi Koki Co., Tokyo, Japan) at 4000 rpm for 10 min. The supernatant was used for subsequent assays.

Antioxidant activity (DPPH radical scavenging assay)

Antioxidant activity was determined using the DPPH radical-scavenging assay, as described by Gulcin and Alwasel (2023). A DPPH solution was prepared in methanol and protected from light. Sample extract (1 mL) was mixed with DPPH solution (3 mL), incubated in the dark at room temperature, and absorbance was measured at 517 nm using a UV–visible spectrophotometer (AE-S90-MD, A&E Lab Instruments, China). Methanol served as the blank, and the DPPH solution without a sample served as the control. Radical scavenging activity was calculated as:

$$DPPH\ radical\ scavenging\ activity\ (\%) = \frac{(Ac - As)}{Ac} \times 100\%$$

Where; A_c: Absorbance of the control, and A_s: Absorbance of the sample Eq. 1

Total phenolic content

Total phenolic content was determined using the Folin–Ciocalteu method (Hatami *et al*., 2014). Gallic acid was used as the reference standard. The sample extract was reacted with diluted Folin–Ciocalteu reagent, followed by the addition of sodium carbonate, and incubated in the dark at room temperature. Absorbance was measured at 760 nm by using a UV-visible spectrophotometer (AE-S90-MD, A&E Lab Instruments, China). Results were calculated from the gallic acid standard curve and expressed as mg gallic acid equivalents per litre; mg (GAE)/L.

Ascorbic acid content

Ascorbic acid content was determined using the DCPIP dye titration method following extraction in 2.5% metaphosphoric acid as described by Ugbe *et al.* (2017). Standardization was performed using L-ascorbic acid, and the endpoint was identified by the appearance of a faint pink colour persisting for 15 s. Results were expressed as mg/100 mL.

Total plate count

Microbiological quality was assessed using the total plate count method in accordance with Sri Lanka Standard SLS 516: Part 1. Degassed samples were serially diluted in sterile saline diluent, plated on Plate Count Agar supplied by laboratory stock (HiMedia Laboratories Pvt. Ltd., Mumbai, India) using the pour plate method, and incubated at 34 °C. Colonies were counted and expressed as colony-forming units per millilitre (CFU/mL).

pH stability during storage

The selected soda formulations were stored at 4 °C, 25 °C, and 40 °C, and pH was monitored weekly to evaluate the effect of storage temperature on product stability.

Statistical analysis

All analyses were performed in triplicate (n = 3). Physicochemical, bioactive, and shelf-life data were analysed using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). One-way analysis of variance (ANOVA) was used to determine significant differences among treatments. Where significant effects were detected, Dunnett's test was applied to multiple comparisons, with the commercially available cola beverage as the reference control. For microbial stability, paired comparisons were performed to compare week 1 and week 2 values with the corresponding week 0 baseline for each formulation. Statistical significance was established at $p < 0.05$.

Sensory data obtained during sweetener selection were analyzed using IBM SPSS Statistics version 22 (IBM Corp., Armonk, NY, USA). Because hedonic scores were non -parametric, the Friedman test was used to detect differences among the three sweetening treatments within each formulation, followed by the Wilcoxon signed-rank test for pairwise comparisons.

RESULTS AND DISCUSSION

Selection of the most acceptable sweetening system for each herbal soda formulation

Coriander-based functional soda

The sensory screening of the coriander-based functional soda indicated that the sugar–stevia blend (T3) achieved the highest mean rank for taste (2.23) and overall acceptability (2.23) among the three sweetening systems evaluated (Table 2). Significant differences were observed in taste and overall acceptability ($p < 0.05$), whereas appearance, mouthfeel, and aroma/odour did not differ significantly among treatments ($p > 0.05$). These findings suggest that the perceived sweetness profile, rather than visual or aromatic attributes, primarily influenced consumer preference in this formulation.

Table 2: Sensory screening of coriander-based functional soda formulated with different sweetening systems (Friedman mean ranks, n = 35)

Sensory attribute	Honey (T1)	Stevia (T2)	Sugar–stevia blend (T3)
Appearance	2.29[a]	1.77[b]	1.94[a]
Taste	1.61[c]	2.16[b]	2.23[a]
Mouthfeel	1.71[a]	2.07[a]	2.21[a]
Aroma/Odour	1.70[a]	2.11[a]	2.19[a]
Overall acceptability	1.63[c]	2.14[b]	2.23[a]

Values are expressed as Friedman mean ranks.
Within each row, values with different superscript letters are significantly different at $p < 0.05$ (Friedman test followed by Wilcoxon signed-rank test)

The superior performance of the sugar–stevia blend may be attributed to the sensory synergy between sucrose and high-intensity sweeteners, whereby partial sugar replacement can maintain sweetness quality while reducing the lingering bitterness or metallic aftertaste often associated with stevia -only systems. This is particularly relevant in coriander-based beverages, where the herbal-citrus sensory profile is shaped by volatile terpenoids, especially linalool, a major constituent of coriander seed aroma (Al-Khayri *et al.*, 2023). Thus, partial sugar replacement appears to provide a more balanced perception of sweetness while preserving the characteristic botanical flavour profile.

Overall, these findings indicate that partial substitution of sugar with a stevia blend offered the best sensory compromise, supporting its selection for subsequent physicochemical, functional, and storage stability analyses.

Tamarind-based functional soda

Among the tamarind-based soda treatments, the sugar–stevia blend (T3) consistently recorded the highest mean ranks for all sensory attributes, including appearance, taste, mouthfeel, aroma/odour, and overall acceptability (Table 3). Importantly, all sensory attributes differed significantly among treatments ($p < 0.05$), indicating that sweetener choice had a stronger impact on the sensory quality of the tamarind matrix than in the coriander-based formulation.

Table 3: Sensory screening of tamarind-based functional soda formulated with different sweetening systems (Friedman mean ranks, n = 35)

Sensory attribute	Honey (T1)	Stevia (T2)	Sugar–stevia blend (T3)
Appearance	2.09^{b}	1.59^{c}	2.33^{a}
Taste	1.24^{c}	1.91^{b}	2.84^{a}
Mouthfeel	1.33^{c}	1.93^{b}	2.74^{a}
Aroma/Odour	1.20^{c}	1.94^{b}	2.86^{a}
Overall acceptability	1.24^{c}	1.83^{b}	2.93^{a}

Values are expressed as Friedman mean ranks.
Within each row, values with different superscript letters are significantly different at $p < 0.05$

This pronounced effect is likely to be associated with the inherently high acidity and astringency of tamarind, which require careful modulation of sweetness to achieve an acceptable flavor balance. Furthermore, tamarind pulp contains appreciable levels of organic acids, particularly tartaric acid, which contribute to its characteristic sour taste (Gupta *et al*., 2025). Under such conditions, stevia-only sweetening may inadequately mask acidity and may accentuate lingering off-notes, whereas the sugar–stevia blend likely improved sweetness onset, temporal profile, and flavor roundness. The notably highest overall acceptability mean rank (2.93; $p < 0.05$) observed for T3 indicates that partial caloric sweetening remains important in highly acidic botanical carbonated beverages, even when sugar reduction is a key formulation objective. This is consistent with beverage reformulation studies demonstrating that partial sugar replacement often outperforms complete sugar replacement in acidic matrices due to superior flavour masking and mouthfeel retention (Majchrzak *et al*., 2015).

Green apple–based functional soda

For the green apple-based functional soda, the sugar–stevia blend (T3) again yielded the highest mean ranks across all sensory attributes, confirming its superiority as a sweetening system across all three formulations (Table 4). Significant differences were observed for taste, mouthfeel, aroma/odour, and overall acceptability ($p < 0.05$), while appearance was not significantly affected by sweetener type ($p > 0.05$).

Table 4: Sensory screening of green apple–based functional soda formulated with different sweetening systems (Friedman mean ranks, n = 35)

Sensory attribute	Honey (T1)	Stevia (T2)	Sugar–stevia blend (T3)
Appearance	2.14^{a}	1.54^{b}	2.31^{a}
Taste	1.93^{b}	1.73^{c}	2.34^{a}
Mouthfeel	1.90^{b}	1.86^{c}	2.24^{a}
Aroma/Odour	1.90^{b}	1.77^{c}	2.33^{a}
Overall acceptability	1.91^{b}	1.66^{b}	2.43^{a}

Values are expressed as Friedman mean ranks.
Within each row, values with different superscript letters are significantly different at $p < 0.05$

Green apple-based beverages typically have a relatively familiar, consumer-friendly flavour profile due to the presence of malic acid, a major determinant of apple acidity and flavour quality (Zhang *et al*., 2026). Because the fruit matrix already provides a naturally appealing flavour base, sweetness perception and aftertaste likely played a greater role in differentiating treatments than visual appearance. The significantly higher mean ranks ($p < 0.05$ each) for taste and overall acceptability in T3 suggest that partial sugar replacement preserved the unique, fruity identity of green apple while mitigating the bitterness commonly associated with stevia-only systems.

Collectively, the sensory findings across all three formulations demonstrate that the sugar–stevia blend provided the most consistently acceptable sweetness profile, and was therefore appropriately selected for further characterization.

Physicochemical characterization of herbal carbonated sodas

The physicochemical properties of the selected functional sodas differed significantly ($p < 0.05$) from the commercial cola reference, reflecting the compositional effects of using plant-derived extracts, reduced-sugar sweetening systems, and mild carbonation (Table 5). In general, the formulated beverages exhibited higher pH, lower total soluble solids, lower total and reducing sugar contents, markedly reduced sodium levels, and substantially lower carbonation than the cola control. These characteristics are consistent with the intended development of reduced-sugar, plant-based functional alternatives to conventional soft drinks.

Table 5: Physicochemical properties of Ayurveda-inspired functional sodas compared with a commercial cola reference

Parameter	Cola (Control)	Coriander soda	Tamarind soda	Green apple soda
pH	2.63 ± 0.18^{c}	4.76 ± 0.02^{a}	2.70 ± 0.01^{c}	3.01 ± 0.01^{b}
Total soluble solids (°Brix)	10.08 ± 0.15^{a}	4.29 ± 0.01^{d}	6.04 ± 0.01^{b}	4.63 ± 0.01^{c}
Total sugar (g/100 mL)	10.51 ± 0.23^{a}	4.52 ± 0.00^{d}	7.85 ± 0.66^{c}	9.02 ± 0.00^{b}
Reducing sugar (g/100 mL)	10.51 ± 0.23^{a}	2.27 ± 0.05^{d}	3.42 ± 0.00^{c}	6.17 ± 0.36^{b}
Titratable acidity (%)	0.0179 ± 0.0004^{c}	0.0023 ± 0.0007^{d}	0.0374 ± 0.0009^{a}	0.0194 ± 0.0003^{b}
Crude fat (% w/w)	0.18 ± 0.04^{b}	0.25 ± 0.06^{b}	1.01 ± 0.06^{a}	0.035 ± 0.06^{b}
Crude protein (% w/w)	0.10 ± 0.00^{d}	1.80 ± 0.73^{b}	3.77 ± 1.68^{a}	0.58 ± 0.40^{c}
Sodium (mg/L)	51.23 ± 0.34^{a}	8.31 ± 0.22^{b}	3.35 ± 0.07^{b}	1.50 ± 0.024^{b}
Carbonation (volumes CO_2)	3.74 ± 0.11^{a}	1.13 ± 0.01^{b}	1.14 ± 0.02^{b}	1.08 ± 0.04^{b}

Values are mean ± SD (n = 3)
Within each row, means with different superscript letters differ significantly at $p < 0.05$ (one-way ANOVA followed by Dunnett's test against the cola control). The physicochemical parameters reported for the commercial cola beverage, which served as the reference control, were obtained from analyses conducted with the same analytical procedures and instruments used for the developed soda formulations

pH and titratable acidity

The coriander-based soda showed a significantly ($p < 0.05$) higher pH (4.76 ± 0.02) than the commercial cola (2.63 ± 0.18), indicating a considerably less acidic matrix. This is technologically and nutritionally relevant, as lower acidity may reduce erosive potential and improve consumer tolerance compared with highly acidified carbonated soft drinks (Barac *et al*., 2023). The higher pH of the coriander beverage is most plausibly explained by the lower total acid load and the buffering capacity of the botanical extract matrix, rather than the direct effect of individual phytochemicals alone. Although coriander seeds are rich in volatile terpenoids such as linalool (Al-Khayri *et al*., 2023), beverage pH is determined more directly by the overall acid–base balance of the formulation, including compounds of betalains, chlorogenic acid from beetroot (Deseva *et al*., 2020), phytosterols and tocols from barley seeds (Idehen *et al*., 2017) and polyphenols like gingerols from ginger (Mao *et al*., 2019).

The green apple soda also showed a significantly higher ($p < 0.05$) pH (3.01 ± 0.01) than cola, despite apples being a known source of malic acid, which is a principal contributor to apple acidity and flavour quality (Zhang *et al*., 2026) and ursolic acid and rosamarinic acid, which are contributing to pharmacological activities of tulsi leaves (Sharma and Singh, 2026). This apparent contradiction highlights an important formulation principle: pH is governed not only by the identity of the dominant acid, but also by total acid concentration, dissociation behaviour, and buffering interactions with other soluble constituents. Thus, although malic acid contributes to the sensory sharpness of the green apple soda, the overall formulation remained less acidic than the phosphoric acid-dominant cola system.

By contrast, the tamarind soda (pH 2.70 ± 0.01) was not significantly different from the cola control ($p > 0.05$) and remained the most acidic of the three herbal formulations, consistent with the high organic acid content of tamarind, particularly tartaric acid (Gupta *et al*., 2025) which was supplemented with dried ashwaganda (*Withania somnifera*) roots; a good source of phenolic compounds and flavonoids (Singirala *et al*., 2025). This interpretation is supported by the titratable acidity data, which showed that tamarind soda had the highest acidity (0.037 ± 0.001%), followed by green apple soda and cola. In comparison, coriander soda exhibited the lowest titratable acidity (0.002 ± 0.001%). Importantly, pH and titratable acidity should be interpreted together, as pH reflects free hydrogen-ion activity, whereas titratable acidity represents the beverage's total acid-neutralisation capacity (Barac *et al*., 2023).

Total soluble solids and sugar profile

All three functional sodas showed significantly lower ($p < 0.05$) total soluble solids than the cola control ($p < 0.05$), with values ranging from 4.29 to 6.04 ^{o}Brix compared with 10.08 ^{o}Brix for cola. This is consistent with the use of a sugar–stevia blend, which reduced the need for added sucrose while preserving sensory acceptability. Similarly, both total sugar and reducing sugar contents were significantly lower ($p < 0.05$) in the formulated functional sodas than in cola, confirming that the beverages achieved a materially reduced sugar load relative to the conventional carbonated soft drink benchmark.

From a nutritional perspective, these results are among the strongest findings of the study, as reduced total soluble solids (4.29 – 6.04 ^{o}Brix vs 10.08 ^{o}Brix) and lower fermentable sugar content (2.27 – 6.17 g/100 mL vs 10.51 g/100 mL) align with current public health and consumer demand for reduced-sugar beverages. However, the green apple soda still contained 9.02 g/100 mL of total sugar, which was relatively close to the value for the commercial cola reference beverage used as the control (10.51 g/100 mL). This suggests that intrinsic fruit sugars contributed substantially to the final sugar content despite limited external sugar addition.

Fat, protein, and sodium contents

As expected for aqueous plant-based beverages, the formulated sodas exhibited low crude fat content overall. However, the tamarind soda showed a numerically higher fat value (1.01 ± 0.06%) than the other beverages and the cola control.

Protein contents were generally low (0.58 – 3.77 % w/w), which is consistent with the beverage format. If confirmed analytically, the relatively higher values in the coriander (1.80 ± 0.73 % w/w) and tamarind formulations (3.77 ± 1.68 % w/w) may be attributable to extractable solids from seeds and roots. At the same time, minor protein contributions from dried tulsi leaves may explain the value observed in the green apple soda. Nevertheless, the protein data should be interpreted conservatively, as such beverages are not intended to function as meaningful protein delivery systems.

Sodium concentrations were markedly lower (1.05 – 8.31 mg/L) in all functional sodas than in cola (51.23 ± 0.34 mg/L), which is an important nutritional advantage. Since no external salt was added, sodium likely originated only from intrinsic plant material and processing water. This lower sodium profile may improve the health positioning of the beverages, particularly for consumers seeking alternatives to conventional soft drinks (Cradock *et al*., 2022).

Carbonation level

All herbal sodas exhibited significantly lower ($p < 0.05$) carbonation levels (1.08 – 1.14 volumes CO_2) than the cola control (3.74 volumes CO_2). Rather than representing a limitation, this appears to reflect an intentional formulation strategy. This lower carbonation level may be advantageous in botanical beverages, as excessive carbonation can accentuate acidity, suppress delicate herbal aromas, and create a harsh sensory bite that may be undesirable in wellness-oriented products. The lower carbonation levels therefore likely contributed positively to flavour retention and sensory harmony, although future studies could further optimize carbonation intensity in relation to consumer preference and aroma release (Sternini, 2013).

Bioactive compound profile and functional potential

The three herbal carbonated sodas exhibited markedly improved bioactive profiles (6.279-20.99 mg/100 mL; ascorbic acid content, 192.25-374.27 mg GAE/L; total phenolic content, 7.53-58.58 %; antioxidant activity) relative to the commercial cola reference, particularly with respect to ascorbic acid content and total phenolic content (Table 6). These findings support the premise that incorporation of botanicals and fruit-derived ingredients can shift carbonated beverages from purely hedonic products toward a more function-oriented nutritional profile.

Table 6: Bioactive properties of Ayurveda-inspired functional sodas compared with a commercial cola reference

Bioactive parameter	Cola (Control)	Coriander soda	Tamarind soda	Green apple soda
Ascorbic acid (mg/100mL)	3.471±0.078[c]	6.279±1.359[b]	8.553±3.563[b]	20.993±4.665[a]
TPC (mg GAE/ L)	31.91±1.30[c]	192.25±4.00[b]	374.27±11.50[a]	195.15±23.36[b]
Antioxidant activity (%)	12.45±0.16[c]	58.58±2.13[a]	25.64±5.55[b]	7.53±1.74[c]

TPC: Total phenolic content, Values are mean ± SD (n = 3). Within each row, means with different superscript letters differ significantly at $p < 0.05$ (one-way ANOVA followed by Dunnett's test against the cola control). The bioactive parameters reported for the commercial cola beverage were obtained from the analyses using the same analytical procedures and instruments employed for the developed soda formulations.

Ascorbic acid content

All three functional sodas contained significantly higher ascorbic acid levels than the cola control ($p < 0.05$), with the green apple soda showing the highest concentration (20.993 ± 4.665 mg/100 mL). This is nutritionally meaningful. Based on adult Recommended Dietary Allowances (RDA) of 75 mg/day for women and 90 mg/day for men, a 100 mL serving of the green apple soda would provide approximately 28.0% and 23.3% of the RDA, respectively, while a 250 mL serving would provide approximately 70.0% and 58.3%, assuming minimal storage losses (Institute of Medicine, 2000).

These findings indicate that green apple formulation may provide a meaningful dietary source of vitamin C. However, because ascorbic acid is highly sensitive to oxygen, light, and thermal degradation (Yin *et al*., 2022), the initial analytical value should not be assumed to remain stable throughout storage. Consequently, future work should include studies of ascorbic acid retention during shelf life, particularly across different storage temperatures and packaging conditions.

Total phenolic content

Total phenolic content was significantly elevated ($p < 0.05$) in all three herbal sodas compared to the cola reference beverage used as the control, with tamarind soda exhibiting the highest phenolic concentration (374.27 ± 11.50 mg GAE/L). This suggests that tamarind and its associated botanical components were particularly effective in enriching the beverage with phenolic compounds. The magnitude of this increase is important because phenolic compounds in plant-based beverages are widely associated with antioxidant, anti-inflammatory, and potential cardiometabolic benefits (Sarkar *et al*., 2022).

Nevertheless, total phenolic content should not be interpreted as a direct measure of biological activity or phenolic identity. The Folin–Ciocalteu assay is best understood as a measure of overall reducing capacity rather than a specific quantification of phenolics alone, because other reducing compounds, such as ascorbic acid, may also contribute to the assay response (Hatami *et al*., 2014).

Therefore, while the total phenolic content data clearly indicate greater phytochemical richness in the herbal sodas than in cola, they should be discussed as an index of phenolic enrichment rather than definitive evidence of functional efficacy.

Antioxidant activity

The DPPH radical-scavenging results revealed a more complex antioxidant profile than indicated by total phenolic content alone. Although tamarind soda exhibited the highest total phenolic content, coriander soda demonstrated the highest DPPH scavenging activity (58.58 ± 2.13%), suggesting that antioxidant performance was influenced not only by total phenolic concentration but also by the chemical structure, redox properties, and reactivity of the compounds present. The antioxidant activity of the coriander-based soda may be attributed to the presence of nitrogen-containing pigment; betalains from beetroot (Deseva *et al*., 2020), phytochemicals; flavonoids, tocols, phytosterols from barley seeds (Idehen *et al*., 2017) and phenolic compounds; gingerols, shogaols from dried ginger (Mao *et al*., 2019). This observation is consistent with previous reports showing that total phenolic content does not always correlate directly with DPPH activity in complex food systems (George *et al*., 2022). In addition, the DPPH assay has recognized methodological limitations, including interference from pigments, sensitivity to antioxidant-to-radical ratio, and possible underestimation of activity under non-optimized conditions (Yeo and Shahidi, 2019). These factors may explain the strong radical scavenging capacity of coriander soda despite its lower total phenolic content. Conversely, the moderate DPPH activity of tamarind soda and the low DPPH response of green apple soda, despite higher phenolic and ascorbic acid levels, indicate matrix-related effects and assay-specific differences in reactivity. Therefore, the three beverages demonstrated distinct functional profiles, highlighting the importance of using multiple antioxidant assays for comprehensive characterization of functional beverages (Munteanu and Apetrei, 2021).

Microbiological stability during refrigerated storage

The total plate count results indicated that all three herbal carbonated soda formulations remained microbiologically stable during 14 days of refrigerated storage, with no significant increase ($p > 0.05$) in viable counts, which decreased slightly from 730–1000 CFU/mL at baseline to 590–600 CFU/mL after two weeks (Table 7). This short-term stability can likely be attributed to the combined preservative effects of multiple hurdles, including low pH, particularly in the tamarind and green apple formulations, dissolved carbon dioxide, prior thermal extraction, refrigerated storage, and sealed aluminium packaging that restricts oxygen ingress and post-processing contamination. Such combined hurdle effects are well recognized in acidic beverage systems, where low pH and temperature suppress microbial proliferation and carbonation may further inhibit spoilage organisms (Dippong *et al*., 2025). However, based on total plate count data alone, it is more scientifically rigorous to conclude that the beverages demonstrated short-term microbiological stability under the tested conditions, rather than broader commercial microbiological safety. Future studies should therefore include yeast and mould enumeration, coliform testing, and extended shelf-life or microbial challenge studies, as acidic, reduced-sugar botanical beverages may still be vulnerable to spoilage by acid-tolerant yeasts, moulds, and other specialized microorganisms during storage (FDA, 2024; Dippong *et al*., 2025).

Table 7: Total plate count of Ayurveda-inspired functional sodas during 2-week refrigerated storage

Formulation	Week 0 (CFU/mL)	Week 1 (CFU/mL)	Week 2 (CFU/mL)
Coriander soda	1000 ± 95.46[a]	970 ± 264.01[a]	600 ± 214.96[a]
Tamarind soda	730 ± 183.84[a]	690 ± 53.74[a]	610 ± 127.28[a]
Green apple soda	950 ± 25.45[a]	880 ± 98.99[a]	590 ± 28.28[a]

Values are mean ± SD (n = 3). Within each row, means sharing the same superscript letter are not significantly different at $p < 0.05$ (paired t-test vs week 0)

pH evolution during storage

Across all three formulations, pH increased progressively during storage, with the most rapid change observed at 40 °C and the smallest change at 4 °C (Figures 1a-c). This temperature-dependent pattern is consistent with established deterioration kinetics in beverage systems, where elevated temperatures accelerate the degradation of organic acids and alter buffering systems, collectively reducing product stability over time (Güler and Tokuşoğlu, 2024). In the present study, pH was used as a practical indicator of quality deterioration; however, pH should be regarded as an indirect quality indicator (Park *et al*., 2014), as it does not fully capture other critical quality attributes such as sensory acceptability, colour stability, carbonation retention, nutrient degradation, or microbiological status. The Arrhenius model is widely applied in accelerated shelf-life testing (ASLT) to estimate shelf life based on temperature-accelerated deterioration kinetics, including studies in which pH has been treated as a critical quality parameter in beverages and liquid foods (Bilbie and Ghizdareanu, 2021).

However, recent evidence also indicates that degradation in complex food systems may not always conform perfectly to classical Arrhenius behavior, particularly when multiple quality-loss mechanisms occur simultaneously, or matrix-dependent changes alter reaction pathways (Kong and Singh, 2016). Accordingly, future studies should validate these projections through real-time shelf-life trials under commercial storage conditions, while integrating sensory evaluation, colour and carbonation measurements, vitamin C retention, microbiological analyses, and additional kinetic markers to establish a more robust and industry-relevant shelf-life model for Ayurveda-inspired functional carbonated beverages.

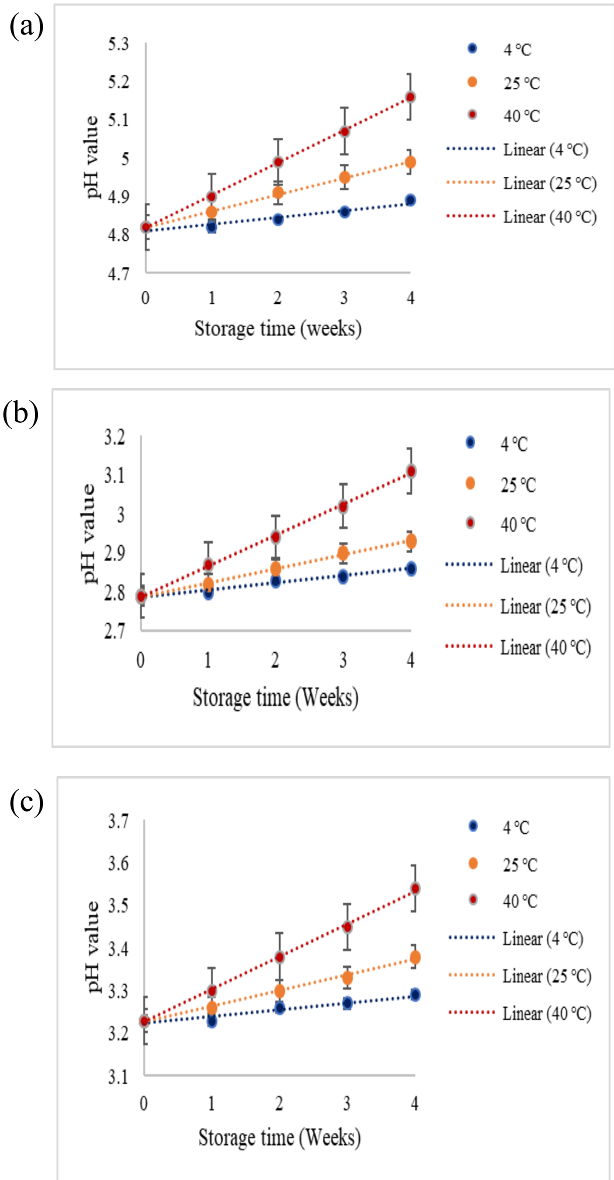

Figure 1. Changes in pH of coriander-based (a), tamarind-based (b), and green apple-based (c) herbal carbonated sodas during storage at 4, 25, and 40 °C. Error bars indicating standard deviation for n=3 replicates

CONCLUSIONS

This study demonstrates that herbal carbonated sodas can successfully integrate traditional botanicals into a carbonated beverage format without compromising sensory appeal. The use of a sugar–stevia blend consistently optimized sweetness perception, ensuring high overall acceptability across all formulations. Compared with the commercial cola reference beverage, the herbal sodas exhibited improved physicochemical profiles, including reduced acidity, lower sugar and sodium content, and mild carbonation, reflecting a health-oriented design approach. Bioactive profiling confirmed enhanced antioxidant potential and phenolic enrichment, highlighting the functional relevance of incorporating plant-derived ingredients. The observed microbiological stability during refrigerated storage supports the feasibility of short-term storage for these formulations. Collectively, these findings validate the potential of combining Ayurvedic knowledge with modern beverage processing to produce clean-label, nutritionally enriched, and functionally relevant carbonated beverages. The study provides a framework for developing novel wellness-oriented soft drinks, bridging traditional botanical wisdom and contemporary consumer expectations.

AUTHOR CONTRIBUTION

GMS and BDRP conceptualized the research project, designed the experiment, and provided supervision and manuscript editing. RGNBB conducted the laboratory experiments, collected and analyzed the data, and prepared the original manuscript.

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