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DEVELOPMENT AND STORAGE STABILITY OF LOW-CALORIE HILL LEMON AND GINGER READY-TO-SERVE (RTS) BEVERAGE

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ABSTRACT

The growing consumer demand for healthier beverages has increased interest in functional drinks with enhanced nutritional benefits. The present study aimed to develop, standardize, and evaluate a low-calorie ready-to-serve (RTS) beverage combining hill lemon (*Citrus pseudolimon* Tan.) and ginger (*Zingiber officinale*) juice blends as a refreshing antioxidant-rich drink. Fresh hill lemon fruits (447 g average weight, 42.7% juice yield, and 4.94% acidity) and ginger juice with high antioxidant activity (72%) but low TSS (3.1°Brix) were used. Three formulations were prepared using different ratios of hill lemon-ginger juice and sweeteners (sugar, sorbitol, honey, and stevia). The highest sensory acceptability was observed for the 85:15 juice ratio with a stevia: sugar (75:25) blend. Nutritional analysis showed that stevia-based formulations significantly reduced sugar content while maintaining antioxidant activity and ascorbic acid. FTIR analysis confirmed functional groups (O–H, C–H, and C–O) associated with key bioactive compounds. During 90 days of storage, acidity, ascorbic acid, antioxidant activity, and sensory quality gradually declined, with glass bottles performing better than PET. Overall, the developed low-calorie hill lemon–ginger RTS beverage shows strong potential as a functional drink for health-conscious consumers and commercial applications.

Keywords: Ginger, hill lemon, low-calorie beverage, ready-to-serve, storage

INTRODUCTION

Citrus fruits (family *Rutaceae*) are among the world's most important fruit crops, grown in over 140 countries and consumed as fresh fruit or processed products such as juices and concentrates (FAO, 2023). In India, citrus ranks third after mango and banana, covering about 1.13 million ha and producing 14.55 million t in 2023-24 (NHB, 2024). They are highly valued for nutrition, being rich in vitamin C, minerals and other health-promoting bioactive compounds (Ahmed and Azmat, 2019).

Hill lemon (*Citrus pseudolimon* Tanaka), locally known as *Galgal*, is an indigenous citrus species of the North-Western Himalayan region, particularly in Himachal Pradesh, Uttarakhand, and parts of Punjab. The fruit is rich in vitamin C, vitamins B-complex, essential minerals, and bioactive compounds such as flavonoids, terpenes, and phenols with functional and therapeutic potential (Kaur *et al*., 2025). Despite its rich nutritional and functional profile, the hill lemon crop has remained confined to the traditional or subsistence-level use, missing opportunities for value addition, product development, and industrial-scale utilization.

In the present study, we prepared a hill lemon juice based ready-to-serve (RTS) beverage by blending it with ginger juice along with various sweeteners. Ginger (*Zingiber officinale*), a member of the *Zingiberaceae* family, is well known for its bioactive constituents such as gingerols, shogaols, paradols, and zingerone, which impart strong antioxidant, anti-inflammatory, antimicrobial, and therapeutic properties (Shalaby *et al.*, 2023; Ayustaningwarno *et al.*, 2024; Matin *et al.*, 2024). Earlier studies have explored that blending citrus juices with plant-based extracts such as ginger, aloe vera, aonla, lemongrass, and mint enhances their nutritional quality and sensory attributes (Chauhan *et al.*, 2012; Rahman *et al.*, 2024). These studies demonstrated improvements in antioxidant potential and flavour profile; however, they often lacked optimization of blending ratios, comprehensive evaluation of low-calorie sweeteners, and detailed analysis of storage stability. Additionally, bitterness development during storage due to limonoids and flavonoid glycosides has not adequately been addressed in most formulations.

The use of alternative sweeteners in RTS beverages has also gained attention due to rising health concerns associated with high sugar intake. While some studies have incorporated sweeteners such as stevia, sorbitol, and honey in fruit beverages, limited research is available on their comparative impact on physicochemical properties, sensory acceptability, and functional stability, particularly in citrus-ginger blends (Liauchonak *et al.*, 2019; Gallagher *et al.*, 2021). Furthermore, the application of advanced analytical tools such as FTIR spectroscopy to characterize functional components in such beverages remains insufficiently explored. Therefore, the present study was undertaken to address these research gaps by developing and standardizing a low-calorie RTS beverage using hill lemon and ginger blends with different sweeteners (sugar, sorbitol, stevia, and honey). Also, the study evaluated the physicochemical, sensory, and antioxidant properties, storage stability and characterized functional groups present. By integrating formulation optimization, low-calorie sweetener application, and advanced analytical evaluation, this work provides a comprehensive approach toward the valorisation of underutilized hill lemon into a functional, consumer-acceptable, and commercially viable beverage.

MATERIALS AND METHODS

Fruit collection and juice extraction

Hill lemon (*Citrus pseudolimon* Tanaka) fruits and ginger (*Zingiber officinale* Roscoe) rhizomes were procured from the local market of Hamirpur, Himachal Pradesh, India in November, 2024. The samples were brought to Department Food Science & Technology, and damaged or spoiled samples sorted out and the remained material was washed under running tap water to eliminate dirt and dust. The juice of fresh hill lemon fruits was extracted after peeling and cutting, followed by processing in a helicoidal screw juicer (SS 304) operated at 45 rpm and 0.3 MPa for 5 min, and subsequently filtered. Similarly, fresh ginger rhizomes were peeled, crushed using a fruit crusher (PSF-121 Senior), and filtered through muslin cloth to obtain the juice.

Physicochemical analysis

The physicochemical characteristics of hill lemon and ginger were measured on ten samples in triplicate using standard protocols. Average fruit and rhizome weights were recorded using an electronic weighing balance (± 0.01 g precision). The vertical and horizontal diameters were measured by a Vernier caliper (least count 0.01 mm), and the fruit/rhizome quotient (V/H ratio) calculated accordingly. Visual characteristics like colour and shape of hill lemon fruits were evaluated using the Royal Horticultural Society (RHS) colour chart (*https://www.scribd.com/document/632767194/RHS-Colour-Charts-editions-pdf*). The number of segments in hill lemon and branches in ginger were counted manually. For yield analysis, fruits/rhizomes were weighed prior to their processing and the individual components including juice, peel, and pomace were separated and weighed using a digital balance. The percentage yield of each component was calculated using the following expression:

$$\text{Yield (\%)} = \frac{\text{Total weight of fruit/rhizome}}{\text{Wieght of component}}\ x\ 100$$

Total soluble solids (TSS) were measured using a digital refractometer (ERMA, Master-S10a) and expressed as °Brix. The pH of juice was determined using a pH meter (Labman LMPH-10). Titratable acidity was estimated using standard titration method (Ranganna, 2020) and expressed in terms of percent citric acid. Reducing, total, and non-reducing sugars were estimated using the Lane and Eynon volumetric method (Ranganna, 2020). Ascorbic acid content was estimated using the 2,6-dichlorophenol indophenol dye titration method (Ranganna, 2020) and expressed as mg 100 g^{-1}. Total phenolic content (mg GAE 100 g^{-1}) was determined using Folin-Ciocalteu method and expressed in terms of mg gallic acid equivalents (GAE 100 g^{-1} sample) [Rizvi *et al*., 2023]. Antioxidant activity was evaluated using DPPH radical scavenging assay (Kedare and Singh, 2011).

Formulations of RTS beverage

The ready-to-serve (RTS) beverages were developed using the blends of hill lemon and ginger juice in four ratios *viz*., 100:0, 95:5, 90:10, and 85:15. Each blend was tested using five sweetener systems *viz*., sugar alone (100%), sorbitol + sugar (1: 1 ratio), stevia + sugar (3:1 ratio), sorbitol + honey (1:1 ratio), and stevia + honey (1:1 ratio). For all formulations, sweetener solutions were adjusted to achieve 10° Brix, 0.3% titratable acidity (as citric acid), 12% fruit juice content as per the specifications of FSSAI (2006). The flow sheet for the preparation process is outlined in Fig. 1.

Hill lemon	Ginger
Fresh hill lemon fruits	Fresh ginger rhizomes
↓	↓
Washing	Washing
↓	↓
Cutting	Peeling
↓	↓
Juice extraction	Crushing
↓	↓
Filtration of Juice	Filtration of Juice

Hill lemon and ginger juice blend preparation (100:0, 95:5, 90:10, & 85:15)
↓
Preparation of sweetener solution (sugar (100%), sorbitol + sugar (1: 1 ratio), stevia + sugar (3:1 ratio), sorbitol + honey (1:1 ratio), and stevia + honey (1:1 ratio))
↓
Mixing juice blend (12%) + Sweetener solution (10° Brix) + 0.3% citric acid adjustment + KMS addition (70 ppm)
↓
Heating and pasteurization (72°C for 15 sec)
↓
Hot filling into sterilized glass bottles
↓
Sealing and cooling

Fig. 1: Flow sheet describing the preparation of RTS formulations

Sensory analysis

The sensory quality of beverages *viz*., colour, texture, taste and overall acceptability were evaluated using a 9-point hedonic scale (Ranganna, 2020). The scale ranged from 1 (dislike extremely) to 9 (like extremely) to capture the panellist's preferences. Ten semi-trained panellists from the Department of Food Science and Technology evaluated the samples in triplicate, and mean scores were analysed using a randomized block design to assess differences among treatments.

Fourier-transform infrared (FTIR) spectroscopy
Best combination of hill lemon-ginger juice ratio, sweetened with different sweeteners, was characterized using FTIR spectroscopy (Agilent Cary 630 FTIR) to determine various functional groups. The analysis was performed in the range of 4000-650 cm^{-1} with a total number of 140 scans per sample. The characteristic peaks were analysed to identify functional groups, structural changes, and possible interactions between juice components and sweeteners (Smith, 2011).

Storage study
For storage studies, the best optimized blended RTS pasteurization at 72°C and packed in glass and polyethylene terephthalate (PET) bottles (n = 18), sealed, and stored at ambient temperature (25-30°C) for 90 days. Physicochemical parameters, including sedimentation rate, haziness, total soluble solids (TSS), titratable acidity, pH, sugars, ascorbic acid, antioxidant activity, and total phenolic content, were analysed at 0, 45, and 90 days of storage intervals.

Statistical analysis
The experiment was conducted in a factorial completely randomized design (CRD) and the results expressed as mean ± standard deviation. Data were analysed using one-way ANOVA for formulation blended RTS and optimization of sweeteners and two-way ANOVA for storage effects, using OPSAT software. Differences were considered significant at $p \leq 0.05$ (Varalakshmi, 2025).

RESULTS AND DISCUSSION

Physicochemical analysis of hill lemon and ginger
The physicochemical characteristics of hill lemon and ginger revealed their complementary roles in beverage formulation (Table 1). Hill lemon exhibited significantly higher fruit weight (447.0 g) and juice yield (42.7%), indicating its suitability as a primary juice base. Its low pH (2.56) and high

Table 1: Physicochemical characteristics of fresh hill lemon and ginger

Characteristics	Parameters	Hill lemon (mean ± SD)	Ginger (mean ± SD)
Physical parameters	Weight (g)	447.00 ± 10.10	43.57 ± 7.12
	Size (cm) (V × H)	11.81 ± 0.30 × 8.97 ± 0.10	6.91 ± 0.34 × 4.77 ± 0.14
	Quotient (V/H)	1.31 ± 0.04	1.48 ± 0.10
	Colour	Yellow	Light brown
	Shape	Ovate oblong	Irregular
	Segments / branches	10.02 ± 0.36	4.29 ± 1.03
	Juice yield (% w/w)	42.70	44.87
	Peel weight (% w/w)	21.34	-
	Seed weight (% w/w)	1.55	-
	Pomace weight (% w/w)	33.71	55.15
Chemical parameters	Total soluble solids (°Brix)	7.20 ± 0.11	3.10 ± 0.08
	pH	2.56 ± 0.01	4.60 ± 0.05
	Titratable acidity (%)	4.94 ± 0.08	0.70 ± 0.01
	TSS/acid ratio	1.45 ± 0.05	-
	Reducing sugars (%)	1.38 ± 0.02	0.80 ± 0.02
	Non-reducing sugars (%)	0.53 ± 0.02	0.27 ± 0.06
	Total sugars (%)	1.94 ± 0.02	1.09 ± 0.06
	Ascorbic acid (mg/100 g)	36.40 ± 0.23	9.20 ± 0.05
	Antioxidant activity (% FRSA)	64.17 ± 0.42	72.03 ± 0.39
	Total phenols (mg GAE100 g^{-1})	3.92 ± 0.01	-

*SD = Standard deviation; V = Vertical diameter; H = Horizontal diameter; n = 10 for physical characteristics and n = 3 for chemical characteristics titratable acidity (4.94%) confirmed its strongly acidic nature, which may be attributed to the presence of organic acids like citric acid, which contribute to flavour, preservation, and microbial stability (Ladaniya, 2008). In contrast, ginger showed a lower rhizome weight but slightly higher juice yield (44.87%) with comparatively higher pH (4.6) and lower acidity (0.7%), indicating a milder acidic profile. The total soluble solids were higher in hill lemon (7.2 °Brix) than ginger (3.1 °Brix), suggesting greater soluble constituents, primarily sugars and acids. Similar compositional differences between citrus fruits and ginger have earlier been reported (Shalaby *et al.*, 2023).

Nutritionally, hill lemon contained higher ascorbic acid (36.40 mg 100 g^{-1}), making it a rich source of vitamin C, whereas ginger exhibited higher antioxidant activity (72.03% FRSA), likely due to bioactive compounds such as gingerols and phenolics. Earlier studies have reported that ginger possesses strong antioxidant activity, mainly attributed to the phenolic constituents like [6]-gingerol and shogaols (Ayustaningwarno *et al.*, 2024). The sugar profile also varied, with hill lemon having higher total sugars (1.94%) compared to ginger (1.09%), contributing to better palatability. Overall hill lemon provides acidity, vitamin C, and flavour, while ginger contributes functional bioactive compounds and antioxidant potential, supporting their combined use in developing value-added functional beverages.

Effect of blending ratios and sweeteners on sensory attributes of RTS

The sensory evaluation of blended RTS beverages combining hill lemon and ginger, sweetened with sugar, sorbitol, honey, and stevia, revealed significant insights into consumer preferences as well as the influence of sweetener types on sensory attributes (Table 2). Across all the sweeteners, sensory scores improved with increasing ginger proportion, with 85:15 hill lemon to ginger ratio consistently achieving highest ratings for colour, taste, flavour, and overall acceptability. This indicates that moderate ginger incorporation enhances flavour complexity by imparting a characteristic pungency that complements citrus acidity. Similar improvements in sensory quality of citrus-based functional beverages with ginger incorporation have been reported by Puranik *et al*. (2013).

Table 2: Sensory evaluation (9-point hedonic scale) of blended RTS beverage of hill lemon and ginger using different sweeteners

Sweeteners	Hill lemon : ginger	Colour	Taste	Flavour	Overall acceptability
Sugar (100%)	100: 0	6.86^{dA}	7.02^{cA}	6.90^{dA}	6.93^{cA}
	95: 5	7.12^{cB}	7.14^{bB}	7.03^{cB}	7.10^{bB}
	90: 10	7.26^{bC}	7.36^{aC}	7.54^{bC}	7.37^{bC}
	85: 15	8.47^{aD}	8.58^{aD}	8.39^{aD}	8.48^{aD}
Sorbitol + sugar (1:1)	100: 0	6.99^{cA}	7.05^{cA}	6.88^{cA}	6.97^{cA}
	95: 5	7.14^{bB}	7.17^{bB}	7.16^{bB}	7.14^{bB}
	90: 10	7.37^{bC}	7.28^{aC}	7.59^{aC}	7.42^{aC}
	85: 15	8.38^{aD}	8.46^{aD}	8.21^{aD}	8.35^{aD}
Stevia + sugar (3:1)	100: 0	7.14^{cA}	7.12^{cA}	7.07^{cA}	7.11^{cA}
	95: 5	7.24^{bB}	7.20^{bB}	7.31^{bB}	7.25^{bB}
	90: 10	7.40^{bC}	7.31^{aC}	7.77^{aC}	7.50^{bC}
	85: 15	8.40^{aD}	8.53^{aD}	8.26^{aD}	8.40^{aD}
Sorbitol + honey (1:1)	100: 0	6.90^{dA}	6.58^{cA}	6.79^{cA}	6.76^{cA}
	95: 5	7.11^{cB}	6.63^{cB}	6.99^{cB}	6.93^{bB}
	90: 10	7.16^{bC}	6.99^{bC}	7.45^{bC}	7.21^{bC}
	85: 15	7.42^{aD}	7.5h2^{aD}	7.71^{aD}	7.56^{aD}
Stevia + honey (1:1)	100: 0	6.82^{dA}	6.86^{cA}	6.88^{cA}	6.86^{cA}
	95: 5	7.02^{cB}	7.04^{bB}	7.13^{bB}	7.07^{bB}
	90: 10	7.10^{bC}	7.17^{bC}	7.50^{bC}	7.30^{bC}
	85: 15	7.29^{aD}	7.42^{aD}	7.69^{aD}	7.45^{aD}

Different lowercase letters in the superscript (a, b, c, d) within rows indicate significant difference between means within each sweetener across the blends as per Duncan's LSD post-hoc test ($p \leq 0.05$); Different uppercase letters in the superscript (A, B, C, D) within rows indicate significant difference between blends (juice ratios) across the sweeteners for the same blend level as per Duncan's LSD post-hoc test ($p \leq 0.05$).

Among the sweeteners, stevia-sugar blend (3:1) gave most favourable sensory outcomes, particularly at 85:15 juice ratio, with overall acceptability reaching 8.40 on a 9-point hedonic scale. The partial replacement of sugar with stevia effectively reduced bitterness and metallic aftertaste commonly associated with high-intensity sweeteners. These findings align with Usman *et al.* (2024), who highlighted the importance of optimizing sweetener combinations to enhance palatability in low-calorie beverages.

The sorbitol-sugar (1:1) blend also demonstrated high acceptability (8.35), likely due to sorbitol's sugar-like taste and its contribution to the improved mouthfeel. Comparable results were reported by Hariharan and Mahendran (2016), who observed that sorbitol-based sweetening maintained desirable sensory properties in ginger-based RTS beverages. In contrast, honey-based blends showed relatively lower acceptability, possibly due to their strong and complex flavour profile, which may not harmonize well with citrus-ginger combinations. Similar trends have been observed in functional beverages where honey enhanced nutritional value but did not consistently improve sensory appeal (Kizzie-Hayford *et al.*, 2024).

Biochemical profiling

The standardized RTS beverage formulated with 85% hill lemon and 15% ginger juice and sweetened with different sweeteners showed significant variation in key quality attributes (Table 3). The highest TSS was recorded in sugar-sweetened beverage (12.0 °Brix), whereas the lowest TSS (7.0 °Brix) was observed in stevia-sugar (3:1) formulation. This reflected the direct contribution of sucrose to soluble solids, while non-nutritive sweeteners like stevia contributed minimal solids despite high sweetening intensity (Goyal *et al.*, 2010; Lemus-Mondaca *et al.*, 2012).

Table 3: Chemical characteristics of standardized blended RTS beverages of hill lemon (85%) and ginger juice (15%) using different sweeteners

Parameters	Sugar (100%)	Sorbitol + sugar (1:1)	Stevia + sugar (3:1)	Sorbitol + honey (1:1)	Stevia + honey (1:1)
TSS (°B)	12.00[a]	11.00[b]	7.00[c]	10.00[ab]	8.00[bc]
pH	3.35[a]	3.31[ab]	3.25[b]	3.58[c]	3.30[ab]
TSS/acid ratio	26.09[a]	22.92[b]	14.00[c]	20.83[ab]	18.18[ab]
Titratable acidity (%)	0.46[c]	0.48[b]	0.50[a]	0.48[a]	0.44[a]
Reducing sugar (%)	7.21[a]	6.11[b]	4.06[c]	6.30[ab]	5.04[bc]
Non-reducing sugar (%)	3.89[a]	3.92[a]	2.00[b]	3.00[ab]	3.80[ab]
Total sugar (%)	11.30[a]	10.24[b]	6.25[c]	7.05[bc]	9.00[b]
Ascorbic acid (mg 100 g^{-1})	3.42[b]	3.46[ab]	3.49[a]	3.48[a]	3.46[a]
Antioxidant activity (%)	6.28[b]	6.33[ab]	6.37[a]	6.27[a]	6.60[a]
Phenols (mg GAE100 g^{-1})	0.38	0.41	0.43	0.42[a]	0.44[a]

Different letters in the superscript (a, b, c) indicate significant difference between sweeteners means according to Duncan's LSD post-hoc test ($p \leq 0.05$)

Titratable acidity ranged from 0.44 to 0.50%, with highest value noticed in stevia–sugar blend. The TSS/acid ratio, an important indicator of flavour balance, was highest in sugar-based beverage (26.09), suggesting a sweeter taste perception, while lower ratio in stevia-based blends indicated a relatively tarter profile. Similar relationships between TSS/acid ratio and sensory perception in fruit beverages have earlier been reported (Saentaweesuk *et al.*, 2025).

The reducing and non-reducing sugars were highest in sugar-only beverage (7.21 and 3.89%, respectively), whereas stevia-based formulations had significantly lower sugar level, confirming their suitability for reduced-calorie beverage development. Previous studies have highlighted the potential of stevia as a sugar substitute in functional beverages without significantly compromising sweetness (Goyal *et al.*, 2010).

The ascorbic acid content showed slight variation (3.42-3.49 mg 100 g^{-1}), with marginally higher values in stevia-containing formulations, possibly due to improved stability of vitamin C.

Comparable findings have been reported where natural sweeteners helped in retaining antioxidant compounds during storage (Lemus-Mondaca *et al.*, 2012).

The antioxidant activity remained relatively stable across the treatments (6.27-6.60%), with highest activity observed in stevia-honey blend, likely due to the combined effect of ginger bio-actives and honey-derived phenolics. Similarly, total phenolic content (TPC) was higher in stevia-based blends (0.43-0.44 mg GAE 100 g^{-1}) compared to sugar-only beverages (0.38 mg GAE 100 g^{-1}), suggesting the positive role of stevia in maintaining phenolic stability. This aligns with earlier reports indicating that natural sweeteners can influence phenolic retention and antioxidant properties in fruit-based beverages (Moldovan and David, 2020).

FTIR spectral profiling

The FTIR spectra of RTS beverages formulated with 85% hill lemon and 15% ginger juice and sweetened with different sweeteners revealed distinct variations in functional groups and molecular composition (Table 4). A broad absorption band observed around 3260-3280 cm^{-1} corresponding to O–H stretching vibrations of hydroxyl groups, indicating the presence of polyphenols, alcohols, and water molecules. Similar observations for hydroxyl groups in fruit-based systems have been reported by Coates (2006) and Amir *et al.* (2013). The higher intensity of this band in sorbitol- and honey-based samples may be attributed to their greater hydroxyl group content.

Table 4: FTIR spectral analysis of standardized blended RTS beverages of hill lemon (85%) and ginger juice (15%) using different sweeteners

Wavenumber (cm^{-1})	Functional group/bond	Assignment	Sugar (100%)	Sorbitol + sugar(1:1)	Stevia + sugar (3:1)	Sorbitol + honey (1:1)	Stevia + honey (1:1)
3400-3200	O–H stretching	Alcohols, phenols (moisture, acids)	Weak	Weak	Absent	Present	Present
2920-2850	C–H stretching	Alkanes (lipids, organic acids)	Absent	Absent	Absent	Moderate	Moderate
1730-1700	C=O stretching	Esters, aldehydes, organic acids	Moderate	Strong	Weak	Strong	Weak
1650-1600	C=C / Amide I	Proteins, polyphenols	Weak	Weak	Moderate	Moderate	Moderate
1450-1370	C–H bending	Lipids, carbohydrates	Moderate	Moderate	Moderate	Moderate	Moderate
1200-1000	C–O stretching	Alcohols, esters, carbohydrates	Moderate	Weak	Strong	Moderate	Moderate
900-700	C–H bending	Aromatic compounds	Weak	Moderate	Strong	Moderate	Moderate

The peaks at 2916-2924 and 2849-2853 cm^{-1} are associated with C–H stretching vibrations of aliphatic $–CH_2$ groups, typically originating from sugars and organic acids. These peaks were more pronounced in sugar-rich formulations, confirming their association with saccharide components, as also reported by Zhang *et al.* (2022). In stevia-honey and stevia-sugar blends, relatively lower intensity in both O–H and C–H regions was observed, likely due to reduced sugar concentration and the presence of steviol glycosides. Peaks around 1645-1656 cm^{-1} correspond to C=C stretching of aromatic compounds and possible amide I bands, indicating the presence of phenolic constituents and minor protein interactions. Similar spectral characteristics of plant-derived bioactives have been reported by Tsotsou and Potiriadi (2022).

A strong absorption band in the region of 1030-1075 cm^{-1} was observed across all the samples, corresponding to C–O stretching vibrations of alcohols, ethers, and carbohydrates. The intensity of this band was highest in sugar alone and sugar-sorbitol blends, reflecting their higher carbohydrate content, which is consistent with standard FTIR interpretations of food matrices (Coates, 2006).

Effect of storage on physicochemical properties of developed RTS beverage

Significant changes were observed in the physicochemical properties of RTS beverage (85:15 hill lemon: ginger) sweetened with stevia-sugar (3:1) during storage, as influenced by both storage duration and packaging material. Sedimentation increased gradually over 90 days in both packaging types, with slightly higher values in PET (0.86) than glass (0.85), though differences were non-significant. This trend may be attributed to natural particle settling and pectin-protein interactions during storage (Sethy *et al.*, 2018). Haziness (% transmittance) increased over time, with PET samples showing marginally higher values, while glass maintained comparatively lower transmittance at later stages, indicating better clarity retention. This may be due to the superior oxygen barrier properties of glass compared to PET (Hopfer *et al.*, 2013).

Table 5: Effect of packaging material on physicochemical characteristics of blended RTS beverage of hill lemon and ginger (85:15) juice using stevia and sugar (75:25) as sweetener during storage

Parameters	Packaging	Storage period		
		0 day	45 day	90 day
Sedimentation rate ((10 cm^{-1}	PET	0.72^{aA}	0.80^{bA}	0.86^{cA}
liquid column)	Glass	0.72^{aA}	0.79^{bA}	0.85^{cA}
Haziness (% transmittance)	PET	1.48^{aA}	1.52^{bA}	1.56^{cA}
	Glass	1.48^{aA}	1.50^{bB}	1.54^{cB}
TSS°B	PET	7.00^{aA}	7.20^{bA}	7.34^{cA}
	Glass	7.00^{aA}	7.06^{bB}	7.11^{cB}
Titratable acidity (%)	PET	0.50^{cA}	0.47^{bA}	0.43^{aA}
	Glass	0.50^{cA}	0.48^{bB}	0.45^{aB}
pH	PET	3.25^{aA}	3.27^{bA}	3.35^{cA}
	Glass	3.25^{aA}	3.27^{bA}	3.33^{cA}
Reducing sugars (%)	PET	4.15^{aA}	4.24^{bA}	4.34^{cA}
	Glass	4.15^{aA}	4.20^{bB}	4.27^{cB}
Non-reducing sugars (%)	PET	1.99^{cA}	1.94^{bA}	1.91^{aA}
	Glass	1.99^{cA}	1.98^{bB}	1.95^{aB}
Total sugars (%)	PET	6.25^{aA}	6.30^{bA}	6.35^{cA}
	Glass	6.25^{aA}	6.28^{bB}	6.32^{cB}
Ascorbic acid (mg100 g^{-1})	PET	3.40^{cA}	3.36^{bA}	3.33^{aA}
	Glass	3.40^{cA}	3.38^{bB}	3.36^{aB}
Antioxidant activity (%)	PET	6.37^{cA}	5.86^{bA}	5.43^{aA}
	Glass	6.37^{cA}	5.98^{bB}	5.54^{aB}
Phenols (mg GAE 100 g^{-1})	PET	0.43^{cA}	0.39^{bA}	0.36^{aA}
	Glass	0.43^{cA}	0.41^{bB}	0.39^{aB}

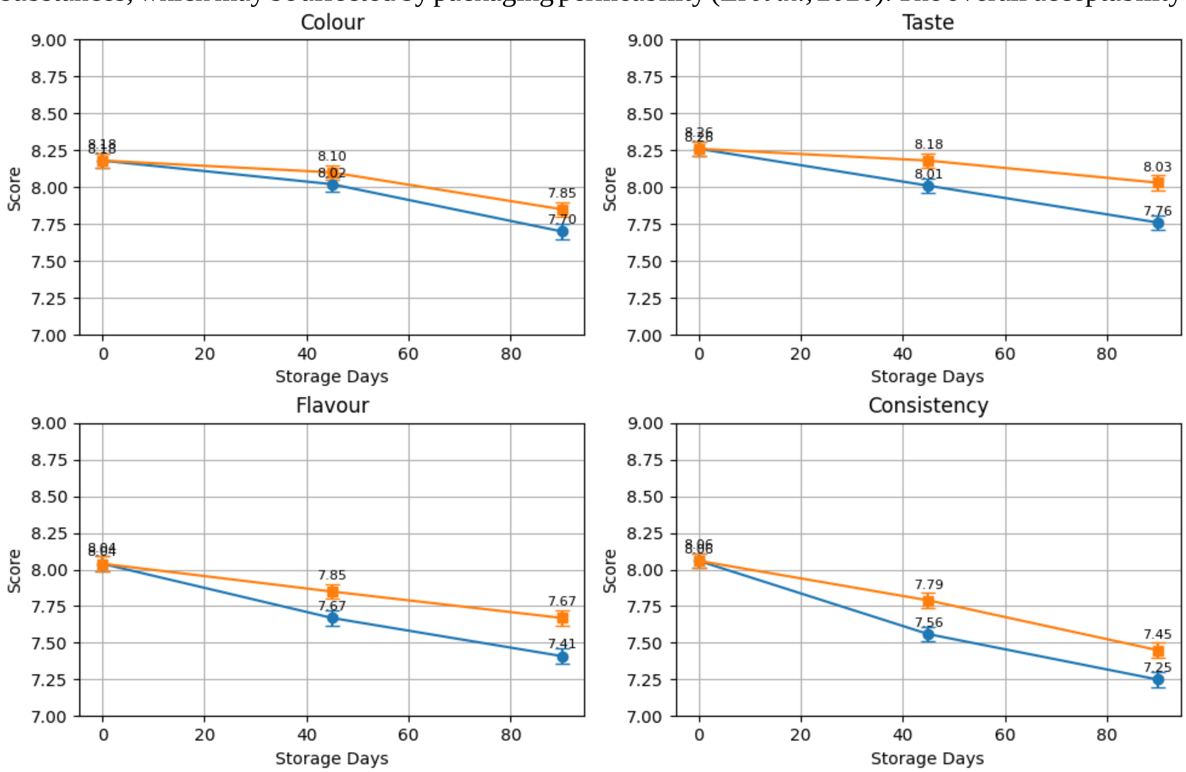
Different lowercase letters in the superscript (a, b, c) within columns indicate significant difference between means within storage intervals (S) as per Duncan's LSD post-hoc test ($p \leq 0.05$); Different uppercase letters in the superscript (A, B) within rows indicate significant difference between packaging types (P) as per Duncan's LSD post-hoc test ($p \leq 0.05$).

Total soluble solids (TSS) showed a gradual increase in both packaging systems, with slightly higher values in PET (7.34 °Brix) than glass (7.11 °Brix), possibly due to moisture loss and sugar hydrolysis. Similar increases in TSS during storage of citrus beverages have been reported by Sonwane and Reshi, (2022). Titratable acidity decreased significantly throughout storage, with a more pronounced decline in PET. This reduction may be linked to volatile acid loss and permeability-related interactions, while glass packaging better preserved acidity due to its inert nature (Westlake *et al.*, 2022). Correspondingly, pH increased over time, showing an inverse relationship with acidity, likely due to degradation of organic acids (Li *et al.*, 2020). Reducing sugars increased steadily, especially in PET, whereas non-reducing sugars lessened, indicating sucrose hydrolysis during storage. This sugar interconversion is commonly observed in fruit-based beverages under ambient conditions (Rao *et al.*, 2009).

Ascorbic acid content declined in all the samples, with slightly higher retention in glass (3.36 mg 100 g^{-1}) compared to PET (3.33 mg 100 g^{-1}) at the end of storage. The degradation is primarily due to oxidation, which is accelerated in PET due to higher oxygen permeability (Jeney-Nagymate and Fodor, 2008). Similarly, antioxidant activity and total phenolic content decreased over storage, with better retention in glass-packaged samples. This highlights the protective effect of glass in preserving bioactive compounds and minimizing oxidative degradation (Mankal *et al.*, 2025).

Effect of storage on sensory quality of developed RTS beverage

The sensory evaluation revealed a progressive decline in colour, taste, flavour, consistency, and overall acceptability of RTS beverages over 90-day storage period (Fig. 2). Colour scores decreased steadily, with a slightly greater decline in PET (8.18 to 7.70) compared to glass (8.18 to 7.85). This reduction may be attributed to the oxidative degradation of pigments such as flavonoids and ascorbic acid derivatives, which are better preserved in glass due to its superior barrier properties against oxygen and light (Hopfer *et al.*, 2013). Similar observations of improved colour stability in glass-packaged citrus beverages have been reported by Westlake *et al.* (2022). Taste and flavour also declined significantly during storage, with higher retention in glass (taste: 8.03; flavour: 7.67) compared to PET (7.76 and 7.41, respectively) at day 90. This may be due to the reduced loss of volatile compounds and better stability of sweeteners in glass packaging. In PET, higher oxygen permeability may accelerate degradation of flavour compounds and enhance undesirable aftertaste, particularly in stevia-based formulations (Rao *et al.*, 2009). Consistency scores decreased over time, more prominently in PET (8.06 to 7.25) than in glass (8.06 to 7.45). This decline could be associated with phase separation and sedimentation of suspended particles such as ginger pulp and pectic substances, which may be affected by packaging permeability (Li *et al.*, 2020). The overall acceptability



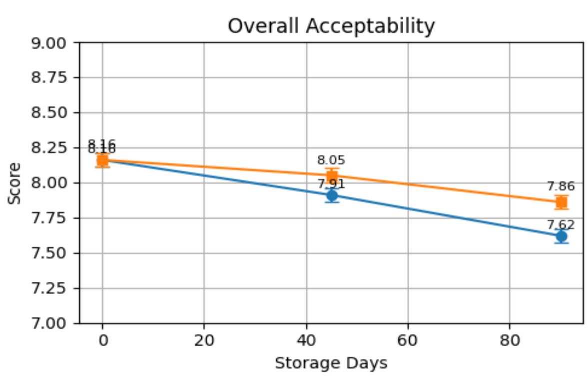


Fig. 2: Effect of packaging material and storage conditions on colour, taste, flavour, consistency and overall acceptability of blended RTS beverage of hill lemon and ginger juice using stevia and sugar (3:1) as sweetener during storage

followed a similar trend, declining from 8.16 to 7.62 in PET and from 8.16 to 7.86 in glass. The comparatively higher retention in glass highlights its effectiveness in preserving sensory quality. These findings are consistent with previous studies reporting better flavour retention and consumer preference for beverages stored in glass containers (Mankal *et al.*, 2025).

Conclusion: The study demonstrated the potential of hill lemon for value addition through the development of a functional RTS beverage with ginger. Hill lemon exhibited high juice yield (42.7%), acidity (4.94%), and ascorbic acid (36.4 mg 100 g^{-1}), while ginger contributed antioxidant activity (72.03%) and functional phytochemicals. A blend ratio of 85:15 (hill lemon: ginger) with a 3:1 stevia-to-sugar sweetener achieved the highest sensory acceptability, offering a health-conscious option without compromising flavour or nutrition. Nutritional analysis confirmed reduced sugar content alongside retained antioxidant and phenolic levels. FTIR analysis verified the presence of key bioactives and the influence of sweeteners on molecular structure, with stevia and honey enhancing the beverage's functional profile. Storage studies over 90 days showed quality retention, especially in glass packaging, supporting product stability for commercialization. Thus, hill lemon and ginger can be effectively formulated into a nutritious, low-calorie functional beverage, promoting the use of underutilized indigenous fruits in the health beverage sector.

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