Food Chemistry Advances 5 (2024) 100792

Contents lists available at ScienceDirect

Food Chemistry Advances

journal homepage: www.elsevier.com/locate/focha

Enhancing probiotic survival and quality of fermented goat milk beverages with bael (*Aegle marmelos*) fruit pulp

Jithmi Siriwardhana [a,1], D.M.D. Rasika [a,1], Dinusha Yapa [a], W.A.D.V. Weerathilake [a], Hasitha Priyashantha [b,*]

[a] Department of Livestock and Avian Sciences, Faculty of Livestock Fisheries and Nutrition, Wayamba University of Sri Lanka, Makandura, Gonawila 60170, Sri Lanka
[b] Department of Molecular Sciences, Swedish University of Agricultural Sciences, Box 7015, Uppsala SE-750 07, Sweden

ARTICLE INFO

Keywords:
Functional beverage
Lactic acid fermentation
Lacticaseibacillus rhamnosus
Milk-fruit beverage
Viability

ABSTRACT

This study aimed to assess the impact of bael fruit pulp on the viability of probiotic *Lacticaseibacillus rhamnosus* GG (LGG) and some physicochemical properties of bael-goat milk-based beverages during 21 days of refrigerated storage. Bael fruit pulp (BFP) was incorporated into goat milk (GM) at different levels (0 %, 5 %, 10 %, and 20 %), and fermented with LGG combined with conventional yoghurt culture. Products were analyzed at weekly intervals. Fermented GM without bael served as control. Redness (a^*), yellowness (b^*), chroma, and LGG viability were all significantly increased while pH, lightness (L^*), and whiteness were dramatically decreased by the addition of BFP. After 14 days of storage, all fermented milk containing bael exhibited considerably ($p < 0.05$) greater LGG counts than the control. The product containing 20 % bael had the greatest viability counts (7.01 log CFU/mL) at the end of storage. Throughout the storage period, all of the products—including the control—maintained viable probiotic counts of greater than 6 log CFU/mL. The pH of the products decreased over time but was stabilized by bael. In conclusion, the findings demonstrate that goat milk is a perfect vehicle for LGG, and adding bael may boost the fermented goat milk's probiotic viability, physicochemical qualities, and nutritional value, thus improving its overall quality.

1. Introduction

Probiotics are live microorganisms that, when administered in adequate amounts, confer health benefits on the host (Hill et al., 2014). They improve digestive and immune function, and formulations must contain sufficient viable probiotics ($>10^6$ CFU/g at the time of consumption) to deliver health benefits. Probiotics have traditionally been associated with fermented dairy products like sour milk, yoghurt, and cheese. Lactic acid bacteria (LAB) have been used for functional dairy products since ancient times, contributing to flavor, texture, and nutrient value (Ranadheera et al., 2018). *Lacticaseibacillus rhamnosus* GG (LGG) is an exopolysaccharide-producing probiotic strain with numerous health-promoting effects in humans. Recent clinical studies have shown that oral supplementation of LGG is a safer immunomodulatory agent that enhances immune response (Salva et al., 2021), improves glycemic control (Sanborn et al., 2020a), cognitive performance (Sanborn et al., 2020b), and improves health-related quality of life in individuals with attention-deficit/hyperactivity disorder (ADHD) (Kumperscak et al., 2020).

Goat milk and its products are becoming popular as healthy substitutes for cow milk, particularly for infant and elderly nutrition and those with certain gastrointestinal disorders (da Silva Dantas et al., 2022; Guo et al., 2022). Goat milk has higher digestibility, alkalinity, buffering capacity, mineral and vitamin contents, and is hypoallergenic, making it an ideal option for those with cow milk intolerance (Araújo et al., 2022; Ma et al., 2022; Mituniewicz-Małek et al., 2017). It also facilitates the long-term survival of probiotics due to its favourable properties (Ranadheera et al., 2018). Different food matrixes derived from goat milk, such as cheese (Pappa et al., 2022), yoghurt (Costa et al., 2022; da Silva Dantas et al., 2022; Machado et al., 2017; Madhubasani et al., 2020; de Morais et al., 2022), fermented goat milk (Araújo et al., 2022; El-Sayed et al., 2024; Guo et al., 2022; Ma et al., 2022; Mituniewicz-Malek et al., 2017), and drinking yoghurts (Elkot et al., 2023) have been studied as ideal delivery vehicles for viable probiotics. However,

* Corresponding author.
E-mail addresses: jithmiradha@gmail.com (J. Siriwardhana), diland@wyb.ac.lk (D.M.D. Rasika), dinusha.yapa1994@gmail.com (D. Yapa), dammikaw@wyb.ac.lk (W.A.D.V. Weerathilake), hasi.tvp@slu.se (H. Priyashantha).
[1] These authors contributed equally to this work and share the first authorship.

https://doi.org/10.1016/j.focha.2024.100792
Received 20 February 2024; Received in revised form 13 August 2024; Accepted 14 August 2024
Available online 15 August 2024

goat milk and its products often have a unique "goaty" flavour due to its higher contents of short- and medium-chain fatty acids (da Silva Dantas et al., 2022; Guo et al., 2022; Wang et al., 2019). LAB fermentation combined with probiotics has been viewed as an ideal strategy to reduce or mask goaty flavour in goat milk products, improving sensory acceptance (Machado et al., 2017; Mituniewicz-Malek et al., 2017).

The addition of natural flavors and aromas using essences, fruits/fruit extracts, and honey may be an attractive alternative to artificial flavorings for use in the development of novel dairy products (Machado et al., 2017). The addition of fruits has a positive influence on fermented goat milk products as it influences microbial, physicochemical, and sensory properties by improving fruit aroma and reducing or hindering goaty flavor leading to improved appeal of goat milk products to consumers. Accordingly, in recent research, various fruits and fruit-derived products such as giloy (*Tinospora cordifolia*) (Sharma et al., 2024), red jumbo pulp (*Syzygium malaccensis*) (Araújo et al., 2022), Cupussu (*Theobroma grandiflorum*) (Costa et al., 2022), white sapote fruit (*Casimiroa edulis*) (Elkot et al., 2023), strawberry juice (Wang et al., 2019), blue honeysuckle juice (*Lonicera caerulea*) (Ma et al., 2022) have successfully been incorporated into various goat milk products. Further, the addition of fruit juice/pulps into probiotic dairy products is an effective strategy to enhance probiotic viability up to the time of consumption of the product as they modify the pH of the product while providing additional nutrient sources for the growth and survival of the probiotics (Ranadheera et al., 2018).

Bael fruit has been known in the Indian subcontinent since ancient times and has been documented in the Hindu, Buddhist, and Jain literature from Vedic times (1500 BCE to 600 BCE). Bael is a sub-tropical tree that is very hardy and can thrive well under diverse agro-climatic conditions. Bael fruits are spherical, woody, and brittle, and contain a pulp yellow in colour that accounts for about 68 % of the total weight of the fruit. Bael fruit has been used in traditional systems of medicine from time immemorial for relieving constipation, diarrhoea, peptic ulcers, and respiratory infections (Roy et al., 2011). The health benefits of bael fruit have recently been comprehensively reviewed. This review reveals that the bael fruit possesses antimicrobial, anti-cancer, cardioprotective, anti-hyperlipidemic, anti-ulcer, hepatoprotective, radioprotective, wound healing, and anticonvulsant activities, and has proven to have inhibitory effects on diarrhoea, dysentery, and diabetes (Sarkar et al., 2020). Bael fruit pulp, rich in carbohydrates (30–42 %) and dietary fibre (2–7 %), is a valuable source of fermentable substrates for probiotics. Its high phenolic content (87 mg g^{-1} dw), including flavonoid (15.2 mg g^{-1} dw), carotenoids (32.9 μg/g dw), and vitamin C (~26 mg/100 dw), prevents rancidity and colour loss (Sarkar et al., 2020; Sharma et al., 2022). These properties can enhance the growth, metabolism, and survivability of probiotics in bael-incorporated food products. Furthermore, enhanced probiotic growth may increase exopolysaccharide production, improving the buffering ability of the product and ensuring an ideal pH range for better probiotic survivability. Overall, bael fruit pulp offers a promising source for incorporating probiotics into food products. The incorporation of bael has also been reported to enhance the overall acceptability of bael-incorporated food products (Begum et al., 2024; Chaudhary et al., 2023).

Enriching goat milk by incorporating bael fruit pulp can be speculated as an ideal strategy to improve probiotic growth and survival as it provides additional fermentable substrates (total sugars account for 12–20 % of the edible portion) for probiotic metabolism (Roy et al., 2011; Sarkar et al., 2020) and additional protection offered by its antioxidative properties (Charoensiddhi & Anprung, 2008). Incorporation of bael into goat milk matrix may also improve the exopolysaccharide production by LGG leading to increased buffering capacities of the product and thereby minimizing the negative impact of post-fermentation during prolonged storage. Bringing *L. rhamnosus* GG into the bael-goat milk matrix may combine the beneficial effects associated with it. More importantly, combining goat milk, bael, and the probiotic LGG may enable milk-fruit beverage consumers to enjoy a large array of benefits from a single product. In this context, the current research aimed to determine the effect of bael fruit pulp on the viability of *Lacticaseibacillus rhamnosus* GG and some selected physicochemical properties of bael-goat milk-based beverages over the refrigerated storage of 21 days.

2. Materials and methods

2.1. Materials and chemicals

Goat milk used in the study was obtained from a goats' farm located in Elabadagama, Northwestern Province of Sri Lanka during September and November. The goat breed used to obtain milk was Saanen. Fully-ripen bael fruits were purchased from the local market. Commercial freeze-dried yoghurt starter culture (Yoflex®-L811) and probiotic LGG (nu-trish® LGG®) were purchased from Chr. Hansen (Horsholm, Denmark). De Man Rogosa Sharpe (MRS) media was purchased from HiMedia Laboratories LLC, PA, USA. Vancomycin was obtained from GUFIC®, Gujarat, India.

2.2. Preparation of bael fruit pulp

The fruits were thoroughly washed and deshelled to obtain the flesh inside. The flesh was extracted, mixed with water in a 1: 1 ratio, and stirred thoroughly until obtaining a consistent pulp and then all the seeds were removed. The pulp was then heat treated at 60 °C for 5 min, allowed to cool down to room temperature, and stored in a closed glass container under refrigerated conditions (4 °C) until use. The heat treatment was employed to inactivate oxidative enzymes naturally present in bael fruit pulp as well as for microbial inactivation.

2.3. Preparation of starter culture

Yoghurt starter (containing *Lactobacillus delbrueckii* ssp. *bulgaricus* and *Streptococcus salivarius* ssp. *thermophilus* in 1:1 ratio) and probiotic (*Lacticaseibacillus rhamnosus* GG) were prepared according to the method previously described by Yapa et al. (2023) using skimmed goat milk as the activation medium.

2.4. Preparation of bael-goat milk beverage

Fermented milk was manufactured from whole goat milk by incorporating different levels (0 %, 5 %, 10 %, and 20 %) of bael fruit pulp. Briefly, whole goat milk was heat treated at 80–85 °C for 25 min with constant stirring while adding 2 % (w/v) sucrose. The pasteurized milk was then divided into four 500 mL portions and inoculated with yoghurt culture and probiotic culture (7-8 log CFU/mL) with varying levels of bael fruit pulp (Table 1). The mixes were poured into 85 g polystyrene cups, closed, and incubated at 42 °C until the milk was coagulated (approximately 7 h). After fermentation, all fermented milk formulations were stirred (150 rpm for 3 min) and stored under refrigerated storage (4 °C) until use.

Table 1
Proportion of the bael fruit pulp, yoghurt starter, probiotic (*L. rhamnosus* GG), and goat milk used to prepare experimental beverages.

Treatment	Bael fruit pulp% (w/v)	Starter% (v/v)	Probiotics% (v/v)	Goat milk (mL)
FGM-0	0	2	2	500
FGM-5	5	2	2	500
FGM-10	10	2	2	500
FGM-20	20	2	2	500

2.5. Proximate analysis of bael fruit pulp and goat milk

The proximate compositions (dry matter, moisture, crude protein, crude fibre, ash, and nitrogen-free extract) of bael fruit pulp and whole goat milk were analyzed. The total solids (method 925.23), crude protein (method 939.02), crude fat (method 2000.18), crude fibre (method 978.10), and ashes (method 930.30) were determined using standard methods of AOAC (2012). The lactose content in goat milk was determined by the iodometric method (Fine, 1932). The content of the nitrogen-free extract (NFE) of the bael fruit pulp was estimated by subtracting the sum of the values for crude protein, crude fat, crude fiber, and ashes from hundred.

2.6. Analysis of physicochemical parameters

The pH of fermented goat milk beverages was determined by a digital pH meter (OHAUS, STARTER 3000, US). The titratable acidity of beverage samples was determined by titration method using 0.1 N NaOH and phenolphthalein [2 % (w/v) in ethanol] as the indicator. Before the titration, a sample of 1 mL of each beverage was diluted with 9 mL of distilled water. Titratable acidity was expressed as a percentage of lactic acid using the following equation.

$$\%\ Lactic\ acid = \frac{Volume\ of\ 0.1N\ NaOH\ consumed\ in\ titration\ \times\ 100}{1\ mL\ of\ sample}$$

The instrumental colour parameters were determined using a Minolta chromameter (Model Colour Reader CR-10 Plus, Konica-Minolta INC, JAPAN; measuring head hole 8 mm; illuminant D_{65}; 10° standard observer angle), and the International Commission on Illumination (CIE) L^*, a^*, and b^* values were recorded. The instrument was calibrated on a white standard provided with the instrument. In each replication, measurements were taken at three different random locations. The L^* value indicated the brightness (100 lighter and 0 darker) of the beverage, whilst the a^* value indicated the red/green (positive being redder and negative being greener) and the b^* value indicated the yellow/blue (positive being yellower and negative being bluer). Based on the above colour coordinates, the Chroma (C^*), °hue (h^*), whiteness index (WI), and overall colour change (ΔE^*) were calculated using the following equations (CIE , 2019). All the physicochemical parameters were determined at 1, 7, 14, and 21 days of refrigerated storage.

$$C^* = \sqrt{a^{*2} + b^{*2}}$$

$$h^* = \tan^{-1}\left(\frac{b^*}{a^*}\right)$$

$$WI = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}}$$

$$\Delta E^* = \sqrt{\Delta a^{*2} + \Delta b^{*2} + \Delta L^{*2}}$$

2.7. Determination of probiotic viability

The LGG viability over the refrigerated storage was determined by the pour plate technique. Ten-fold serial dilutions of each product were prepared by suspending 1 g of the fermented beverages in 1 % (w/v) peptone water. The viable LGG count was obtained by selective enumeration of the probiotic bacteria on MRS vancomycin agar (pH 6.2) which contained 50 ppm vancomycin (GUFIC®, Gujarat, India). Plates were incubated at 37 °C for 72 h under anaerobic conditions. Plates containing 20 - 200 colonies were enumerated using a colony counter (Stuart SC6PLUS, Stuart Scientific, UK). The probiotic viability was reported as colony-forming units per milliliter (CFU/mL) of the product. Probiotic viability was determined at 1, 7, 14, and 21 days of refrigerated storage.

2.8. Statistical analyses

All the experiments were duplicated to confirm the repeatability of the results. All the results were reported as mean ± standard deviation (SD) for the triplicate analyses. All the statistical analyses were performed using SPSS version 22.0 (SPSS Inc., Chicago, IL) with a significance level of $p < 0.05$. The effect of treatment and storage time on probiotic viability and physicochemical parameters were evaluated by performing a 2-way mixed ANOVA. The means were separated using the Tukey test. Data were treated as randomized complete blocks arranged in a 4 × 4 factorial scheme (4 treatments: FGM-0, FGM-5, FGM-10, and FGM-20; and four lengths of storage time; 1, 7, 14 and 21 d). The simple main effect for storage time was determined by Multiple Repeated Measures ANOVA. Whereas, the simple main effect for treatment on probiotic viability and physicochemical properties was determined by performing separate one-way ANOVAs at each time point (1, 7, 14, and 21 days). The Pearson correlation coefficients among different variables were calculated using XLSTAT Software (Lumivero, Suite, Denver, CO).

3. Results and discussion

In the current study, we evaluated the effect of bael fruit pulp on certain physiochemical properties and LGG viability over 21 days of refrigerated storage in a fermented goat milk beverage with varying incorporation levels of beal (0, 5, 10, and 20 %). Incorporating bael fruit pulp proportionately decreased pH, lightness (L^*), and the whiteness index (WI). The °hue also showed a decreasing trend but not proportionately to the level of bael incorporated. The yellowness (b^*), chroma (C^*), and the overall colour change (ΔE^*) were increased proportionately to the level of bael incorporated. The redness (a^*) also increased but was not proportionate to the bael concentration. All of these parameters showed varying trends over the storage which have been comprehensively discussed below.

3.1. Composition of goat milk and bael fruit pulp

The proximate compositions of whole goat milk and bael fruit pulp used to produce experimental fermented beverages are displayed in Table 2. Whereas, Fig. 1 depicts ripened beal fruit, bael fruit pulp, and the appearence of fermented beverages before and after fermentation. The whole goat milk contained just over 4 % fat and about 13.5 % total solids. The solid non-fat (SNF) content was about 9.4 % and agreed with already published results (Bruzantin et al., 2016). The crude protein content (3.4 %) was also fallen within the range reported in previous studies (Kavas et al., 2003; Wang et al., 2012). However, the ash content detected in the current study (1.77 ± 0.02) was slightly higher compared with that (0.61–0.91 %) of other published reports (Bruzantin et al., 2016; Costa et al., 2015; Eissa et al., 2010). Lactose content in goat milk was about 4.2 % which was slightly lower than the values (4.85–5.02 %) published in the literature (Costa et al., 2015). The

Table 2
Proximate composition of raw goat milk and bael fruit pulp used to prepare probiotic bael-goat milk beverage (data are mean ± SD).

Item	Goat milk	Bael fruit pulp
Moisture (g/100 g)	85.67 ± 0.32	60.40 ± 0.84
Total solids (g/100 g)	13.43 ± 0.32	39.60 ± 0.84
Crude fat (g/100 g)	4.03 ± 0.06	0.37 ± 0.00
Crude protein (g/100 g)	3.42 ± 0.00	2.34 ± 0.31
Crude fiber (g/100 g)	ND[1]	6.26 ± 0.05
Ash (g/100 g)	1.77 ± 0.02	2.68 ± 0.04
Nitrogen-free extract (g/100 g)	ND[1]	27.5 ± 0.25
Lactose (g/100 g)	4.20 ± 0.26	ND[1]
pH	6.5 ± 0.01	5.00 ± 0.01
Total soluble solids (Brix°)	13.43 ± 0.32	39.60 ± 0.84

[1] ND, not determined.

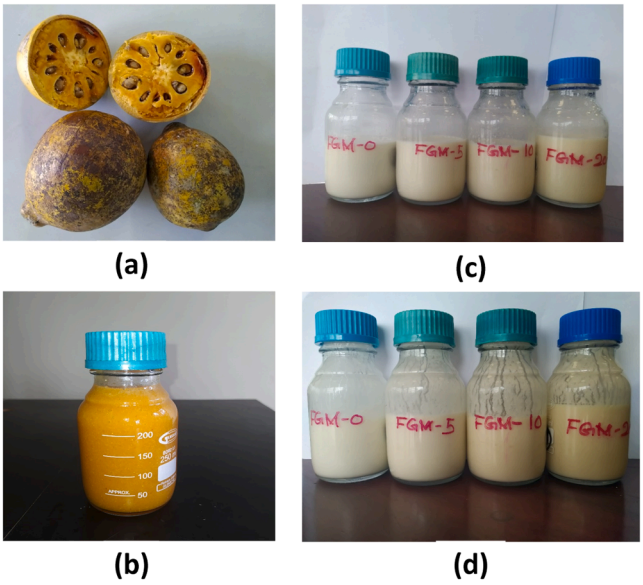

Fig. 1. (a) Ripen beal fruit, (b) Bael fruit pulp, (c) Bael-goat milk beverages before fermentation, and (d) Bael-goat milk beverages after fermentation.

compositional differences in goat milk seen among different publications may be due to season, stage of lactation, breed, diet, variations in the individual animal, and management conditions.

In contrast, the fat content in bael pulp was well below 0.5 % although the total solid content was three times higher than that of the goat milk. More interestingly bael fruit pulp contained just over 6 % of crude fibre which is important as a source of prebiotics during gastrointestinal digestion. Our results for bael fruit pulp were compatible with already published data. Previously published research showed that the moisture, crude protein, crude fibre, and crude fat contents of bael fruit pulp ranged from 61 to 67 %, 1.6 to 3.6 %, 2.2 to 4.8 %, and 0.2 to 0.4 %, respectively (Sarkar et al., 2020; Sharma et al., 2022). The Nitrogen-free extract (NFE) is composed of water-soluble polysaccharides. In the previous studies, the NFE values ranged from 30.5 to 34.4 % which is slightly higher than the values obtained in the current study. Moreover, the value for the total soluble solids (39 Brix°) obtained in our study was also slightly higher than the values (36 Brix°) reported in the already published data. The variations seen among different studies may be due to the differences in cultivars used in the respective studies, the ripening stage, and the agro-climatic conditions they were grown.

3.2. Changes in pH and acidity

The initial pH of the goat milk and beal fruit pulp used to prepare fermented beverages was 6.5 ± 0.01 and 5.00 ± 0.01, respectively. The addition of bael into the goat milk proportionately decreased the initial pH depending on the level of the beal fruit pulp incorporated (pH 6.08, 6.05, and 6.02 in 5 %, 10 %, and 20 % bael incorporated goat milk, respectively). This is because of the natural acidity of the bael fruit pulp that slightly decreased the initial pH. Natural acidity comes from naturally occurring organic acids such as oxalic, malic (0.155 %), tartaric acid (0.215 %), and ascorbic acid (17–27 mg/100 g) as well as phenolic acids (87.34 ± 4.44 mg GAE/g dw) (Charoensiddhi & Anprung, 2008; Ram & Singh, 2003; Sarkar et al., 2020).

Table 3 shows the variation in pH of the products over the refrigerated storage. Statistical analysis revealed that both the storage time (p = 0.000) and type of fermented beverage/treatment (p = 0.000) significantly affect the pH. In addition, there was a statistically significant two-way interaction between storage time × beverage type (p = 0.000). The effect of the addition of bael fruit extract was more prominent even after the first day of refrigerated storage where the pH of the products

Table 3
Variation in the physicochemical characteristics of the probiotic fermented goat milk beverages over 21 days of refrigerated (4 °C) storage.

Variable	Product	Storage period			
		Day 1	Day 7	Day 14	Day 21
pH	FGM-0	5.15 ± 0.05^{c,A}	4.96 ± 0.04^{b,AB}	4.67 ± 0.05^{b,B}	4.36 ± 0.16^{a,B}
	FGM-5	4.94 ± 0.04^{a,A}	4.88 ± 0.05^{b,A}	4.77 ± 0.04^{b,A}	4.30 ± 0.03^{a,B}
	FGM-10	4.70 ± 0.04^{a,A}	4.62 ± 0.02^{a,A}	4.52 ± 0.03^{a,A}	4.25 ± 0.02^{a,B}
	FGM-20	4.60 ± 0.03^{a,A}	4.58 ± 0.03^{a,A}	4.49 ± 0.06^{a,AB}	4.29 ± 0.01^{a,B}
Titratable acidity (% lactic acid)	FGM-0	0.93 ± 0.05^{a,A}	0.99 ± 0.00^{a,A}	1.02 ± 0.05^{a,A}	1.05 ± 0.05^{a,A}
	FGM-5	0.96 ± 0.05^{a,A}	1.02 ± 0.05^{a,A}	1.05 ± 0.05^{a,A}	1.08 ± 0.00^{a,A}
	FGM-10	0.99 ± 0.00^{a,A}	1.02 ± 0.05^{a,A}	1.05 ± 0.05^{a,A}	1.05 ± 0.05^{a,A}
	FGM-20	0.99 ± 0.01^{a,A}	1.05 ± 0.05^{a,AC}	1.08 ± 0.00^{a,BC}	1.08 ± 0.00^{a,BC}
L^*	FGM-0	88.92 ± 4.00^{a,A}	79.82 ± 3.07^{a,A}	83.32 ± 4.22^{a,A}	86.93 ± 2.79^{a,A}
	FGM-5	87.78 ± 3.67^{a,A}	84.25 ± 1.12^{a,A}	85.55 ± 1.99^{a,A}	81.03 ± 0.47^{a,A}
	FGM-10	85.38 ± 0.33^{a,A}	79.81 ± 1.12^{a,BC}	84.78 ± 1.99^{a,AC}	75.31 ± 0.47^{a,AC}
	FGM-20	79.37 ± 3.67^{a,AC}	80.01 ± 3.77^{a,A}	85.85 ± 1.84^{a,BC}	83.11 ± 9.71^{a,AC}
a^*	FGM-0	−2.47 ± 0.12^{a,A}	−3.17 ± 0.04^{a,BC}	−2.15 ± 0.40^{a,AC}	−2.58 ± 0.44^{a,AC}
	FGM-5	−0.67 ± 0.21^{c,A}	−1.16 ± 0.05^{b,A}	0.08 ± 0.34^{b,A}	2.86 ± 0.29^{c,B}
	FGM-10	−1.68 ± 0.22^{b,A}	−0.34 ± 0.05^{c,A}	−0.66 ± 0.34^{b,A}	0.58 ± 0.29^{b,A}
	FGM-20	−1.35 ± 0.22^{b,A}	−1.08 ± 0.29^{bc,A}	−0.47 ± 0.32^{b,A}	0.31 ± 1.34^{b,A}
b^*	FGM-0	5.21 ± 1.15^{a,A}	12.68 ± 1.43^{a,A}	3.95 ± 0.54^{a,A}	8.25 ± 1.32^{a,A}
	FGM-5	8.20 ± 0.85^{a,A}	15.99 ± 0.39^{a,BC}	13.17 ± 5.42^{b,AC}	16.17 ± 0.08^{b,BC}
	FGM-10	12.73 ± 0.85^{b,A}	22.08 ± 0.39^{b,A}	15.26 ± 5.42^{b,A}	16.08 ± 0.08^{b,A}
	FGM-20	24.69 ± 1.49^{c,AD}	27.94 ± 0.92^{c,AC}	17.72 ± 3.76^{b,BC}	18.23 ± 2.83^{b,BD}
C^*	FGM-0	5.78 ± 0.90^{a,A}	13.07 ± 1.14^{a,A}	4.50 ± 0.54^{a,A}	8.66 ± 1.00^{a,A}
	FGM-5	8.23 ± 0.68^{a,A}	16.03 ± 0.32^{a,BC}	13.18 ± 4.4^{ab,AC}	16.42 ± 0.10^{b,BC}
	FGM-10	12.85 ± 1.18^{b,A}	22.08 ± 0.75^{b,A}	15.28 ± 3.05^{b,A}	16.13 ± 2.34^{b,A}
	FGM-20	24/73 ± 0.83^{c,AD}	27.96 ± 2.70^{c,AC}	17.72 ± 1.47^{b,BC}	18.23 ± 2.14^{b,BD}
h^*	FGM-0	115.80 ± 2.97^{b,AB}	104.12 ± 1.12^{c,A}	118.43 ± 1.00^{b,BC}	107.70 ± 3.52^{c,AC}
	FGM-5	94.77 ± 1.64^{a,A}	94.14 ± 0.07^{b,A}	89.69 ± 1.52^{a,AC}	79.97 ± 0.78^{a,BC}
	FGM-10	97.63 ± 1.42^{a,A}	90.90 ± 0.62^{a,A}	92.75 ± 1.57^{a,A}	88.39 ± 3.70^{b,A}
	FGM-20	93.13 ± 0.43^{a,A}	92.22 ± 0.87^{ab,A}	91.59 ± 0.81^{a,A}	89.10 ± 0.57^{b,A}
White Index	FGM-0	87.28 ± 2.41^{b,A}	75.95 ± 2.72^{bc,A}	82.67 ± 3.19^{a,A}	84.32 ± 2.45^{b,A}
	FGM-5	85.21 ± 2.78^{b,A}	77.52 ± 0.71^{c,A}	80.33 ± 4.21^{a,A}	74.91 ± 0.33^{ab,A}
	FGM-10	80.51 ± 0.76^{b,A}	69.97 ± 1.89^{ab,A}	78.32 ± 2.64^{a,A}	70.21 ± 7.08^{a,A}
	FGM-20	67.51 ± 4.2^{a,A}	65.59 ± 2.29^{a,A}	77.30 ± 1.16^{a,AC}	75.07 ± 2.42^{ab,BC}
ΔE^*	FGM-0	-	12.02 ± 1.85^{a,A}	5.82 ± 1.21^{a,A}	5.23 ± 2.48^{a,A}
	FGM-5	6.12 ± 1.24	8.91 ± 1.12^{a,A}	6.69 ± 4.63^{a,A}	11.32 ± 2.19^{a,A}
	FGM-10	9.12 ± 0.83	11.19 ± 2.39^{a,A}	3.62 ± 3.03^{a,A}	12.53 ± 6.33^{a,A}
	FGM-20	23.20 ± 4.04	6.39 ± 3.45^{a,A}	10.55 ± 4.53^{a,A}	9.39 ± 1.96^{a,A}

[a-c]Means within a column with different superscripts are significantly different ($p < 0.05$). [A-C]Means within a row with different superscripts are significantly different ($p < 0.05$). FGM-0 = probiotic fermented goat milk without bael fruit pulp; FGM-5 = probiotic fermented goat milk containing 5 % (w/v) bael fruit pulp; FGM-10 = probiotic fermented goat milk containing 10 % (w/v) bael fruit pulp; FGM-20 = probiotic fermented goat milk containing 20 % (w/v) bael fruit pulp. Data are mean ± SD of three replicates.

containing bael (FGM-5, −10, and −20) was significantly lower than that of the product without bael (FGM-0). At the day-7 and −14 of the refrigerated storage however, the pH values of the product without bael (FGM-0) and the product containing 5 % bael (FGM-5) were comparable and remained higher ($p < 0.05$) than the products containing 10 and 20 % bael. Titratable acidity values followed the same trend where the lowest titratable acidity was found in the product without bael suggesting that the acid production was comparatively higher in the products containing bael. Bael fruit pulp is reported to contain considerable amounts of carbohydrates (30 – 35 %) whereas the total sugars account for 14–20 % (Ram & Singh, 2003; Sarkar et al., 2020). These carbohydrates may provide extra fermentable substances for the growth of starter cultures where their higher metabolic rate results in higher acid accumulation. However, after 21 days of refrigerated storage, the pH values of all four products were comparable ($p > 0.05$).

When the variation in pH of the products throughout the 21 days of storage is concerned, there was a continuous decrease in all formulations and this decline was significant ($p < 0.05$) compared to that of day 1. The largest decline (0.79 points) was observed in the product without beal (FGM-0) followed by FGM-5 (decline of 0.64 points), FGM-10 (decline of 0.45 points), and FGM-20 (decline of 0.31 points). Results showed that this decline was proportionately lower with the increasing inclusion levels of bael suggesting that bael-incorporated products have better buffering capabilities. The product without bael (FGM-0) was subjected to a significant decline in pH much earlier than beal incorporated products (FGM-5, −10, and −20) in which a significant decline in pH was observed only after 21 days of storage. This also confirms the buffering capacity of bael fruit pulp-incorporated fermented goat milk beverages that stabilize the pH during refrigerated storage. Most probably, the reduction in pH during the storage may be due to the continuous acid production by LAB mainly *Lactobacillus bulgaricus* which is known as post-acidification (Araújo et al., 2022; Costa et al., 2022). Similar observations were previously reported in red jumbo pulp-incorporated probiotic goat milk beverages (Araújo et al., 2022), blue honeysuckle juice-incorporated fermented goat milk beverages (Ma et al., 2022), and carob molasses-added fermented goat milk (El-Sayed et al., 2024) in addition to Bifidus goat milk (Mituniewicz-Malek et al., 2017) and goat milk yoghurts with various additives such as skim milk powder (Bruzantin et al., 2016), cupuassu pulp (Costa et al., 2022), polymerized whey protein (Wang et al., 2012) and bee honey (Machado et al., 2017). Eissa et al. (2010) reported pH values as low as 2.67 by 15 days of storage. However, in our study, the pH values remained 4.29 – 4.36 even after 21 days of storage suggesting better buffering capabilities of bael-incorporated beverages that might be resulting from the exopolysaccharides produced by LGG.

The variations in the titratable acidity of the products over the 21 days of refrigerated storage are shown in Table 3. The variation in titratable acidity is likely to be closely associated with decreasing pH values of the products over the storage period. Only the storage time had a significant influence ($p = 0.000$) on the titratable acidity. There was neither a treatment effect ($p = 0.082$) nor a two-way interaction effect of treatment/product type × storage time ($p = 0.974$) on titratable acidity. There were no significant differences ($p > 0.05$) among treatments at each time point of the storage. However, there was an overall increase in titratable acidities of all products over the storage period. This increase was not significant in FGM-0, -5, and -10. Only the product containing 20 % bael fruit pulp showed a significant increase ($p < 0.05$) in titratable acidity from 14 days of storage. This may be because there is an increased supply of fermentable sugars corresponding to the level of bael incorporated. When there is a high amount of fermentable sugars in the media, the chance for post-acidification would be higher as a result of enhanced growth and metabolic activity of the starter cultures. In contrast, the titratable acidities of all four treatments were comparable at each time point (at day-1, -7, -14, and -21) of the storage period ($p > 0.05$).

3.3. Changes in instrumental colour

Colour is one of the most important factors determining consumer acceptance of the product (Ma et al., 2022). In the current study, the changes in the colour values of the products were measured in CIELAB colour space using L^*, a^*, and b^* colour coordinates. L^*, a^*, and b^* values measure the difference in lightness and darkness (+ lighter, - darker), red and green (+ redder and – greener), and yellow and blue (+ yellower and – bluer). Statistical analysis revealed that storage time had a significant effect on all colour parameters tested: L^* value ($p = 0.024$), a^* value ($p = 0.000$), b^* value ($p = 0.000$), chroma ($p = 0.000$), hue ($p = 0.000$), and whiteness index ($p = 0.000$) except ΔE^* ($p = 0.058$). On the other hand, treatment/beverage type had a significant effect ($p < 0.001$) on all colour parameters except the L^* value ($p = 0.220$) and ΔE^* ($p = 0.938$). A significant two-way interaction of storage time × treatment existed on all colour parameters tested ($p = 0.000$ for a^*, b^*, h^*, C^*; $p = 0.036$ for L^*; $p = 0.002$ for whiteness index; and $p = 0.022$ for ΔE^*.

The initial lightness (L^* value) of the goat milk (88.92 ± 4.00) proportionately decreased ($p > 0.05$) with increasing levels of beal pulp incorporated (Table 3). The addition of bael significantly ($p < 0.05$) increased the redness (increasing a^* values) but not proportionately to the level of bael incorporated. Yellowness (increasing b^* values) of the goat milk increased proportionately with increasing levels of bael. However, only 10 % and 20 % incorporation levels made a significant ($p < 0.05$) rise in yellowness. Bael fruit pulp is reported to contain a considerable amount of carotenoids (32.98 ± 0.51) which absorb light and produce the yellow perception (Charoensiddhi & Anprung, 2008). When the beal concentration is increased, this yellow pigment will be increased in the milk which increases the yellowness. The same phenomenon (decreased L^* values, and increased a^* and b^* values) was observed in a honey-incorporated goat milk yoghurt where the values were changed proportionately to the added amount of honey (Machado et al., 2017). Cheng et al. (2019) also reported increased yellowness in a milk-based beverage with increasing fat concentration because the carotenoid content is increased proportionately with increasing levels of fat. Chroma (C^*) is a qualitative attribute of colourfulness. The higher the C^* values, the higher the colour intensity perceived by humans. In the current study, the chroma increased proportionately with the amount of bael added to goat milk. Incorporating bael at 10 % and 20 % made significant ($p < 0.05$) increases in the C^* value. Pearson correlation analysis (Table 4) showed that there was a strong positive correlation between the C^* and b^* values suggesting that increasing chroma was due to the increased b^* values when adding bael. Hue angle (h^*) is a relative attribute of colour and a higher h^* represents a lesser yellow character. Values closer to 0/360° reflects red hue, 90° yellow hue, 180° green hue, and 270° blue hue. In this study, the heat-treated goat milk had an h^* of 115 ± 2.97 which was significantly ($p < 0.05$) shifted towards yellow when bael was incorporated. However, the shift was not concentration-dependent. The h^* values showed a strong negative correlation with the a^* and b^* values (Table 4). Raw goat milk had a white index of 87.21 ± 2.41. Incorporation of 5 % and 10 % bael declined the white index in a concentration-dependent manner although the decline was not significant ($p > 0.05$). Only the incorporation level of 20 % bael significantly ($p < 0.05$) declined the white index of goat milk. The overall colour change was increased with increasing levels of bael incorporation in which the 20 % incorporation made the highest shift in overall colour.

The lightness (L^* values) of the fermented goat milk beverages

Table 4
Pearson correlation matrix of the variables over the storage period of 21 days.

Storage Time	Variables	pH	TA	L-value	a-value	b-value	Chroma	Hue	White Index	Viability
Day 1	pH	**1**								
	TA	−0.599	**1**							
	L-value	0.621	−0.457	**1**						
	a-value	−0.406	0.258	−0.125	**1**					
	b-value	−0.860	0.456	−0.697	0.280	**1**				
	Chroma	−0.853	0.449	−0.698	0.259	**1.000**	**1**			
	Hue	0.782	−0.472	0.384	−0.832	−0.660	−0.642	**1**		
	White Index	0.802	−0.480	0.899	−0.207	−0.937	−0.939	0.551	**1**	
	Viability	−0.816	0.456	−0.751	0.188	0.860	0.858	−0.622	−0.858	**1**
Day 7	pH	**1**								
	TA	−0.478	**1**							
	L-value	0.249	−0.171	**1**						
	a-value	−0.733	0.375	0.107	**1**					
	b-value	−0.897	0.315	−0.247	0.635	**1**				
	Chroma	−0.894	0.310	−0.256	0.621	**1.000**	**1**			
	Hue	0.793	−0.406	−0.049	−0.973	−0.749	−0.737	**1**		
	White Index	0.815	−0.298	0.612	−0.434	−0.915	−0.920	0.555	**1**	
	Viability	−0.311	0.016	0.093	0.699	0.087	0.075	−0.565	0.009	**1**
Day 14	pH	**1**								
	TA	−0.324	**1**							
	L-value	0.027	0.271	**1**						
	a-value	−0.003	0.403	0.284	**1**					
	b-value	−0.523	0.336	0.209	0.734	**1**				
	Chroma	−0.529	0.332	0.204	0.720	**1.000**	**1**			
	Hue	0.210	−0.430	−0.377	−0.949	−0.834	−0.822	**1**		
	White Index	0.540	−0.157	0.424	−0.458	−0.789	−0.794	0.488	**1**	
	Viability	−0.516	0.331	0.228	**0.738**	**0.858**	0.851	−0.861	−0.623	**1**
Day 21	pH	**1**								
	TA	0.201	**1**							
	L-value	0.414	−0.298	**1**						
	a-value	−0.325	0.312	−0.408	**1**					
	b-value	−0.477	0.287	−0.511	0.763	**1**				
	Chroma	−0.465	0.288	−0.510	0.771	**1.000**	**1**			
	Hue	0.486	−0.278	0.456	−0.973	−0.839	−0.842	**1**		
	White Index	0.495	−0.331	0.939	−0.593	−0.774	−0.773	0.661	**1**	
	Viability	−0.455	0.351	−0.284	**0.742**	**0.918**	0.913	−0.821	−0.573	**1**

fluctuated throughout the refrigerated storage (21 d). When comparing the values between days 1 and 21, beverages containing 0 %, 5 %, and 10 % bael (FGM-0, −5, and −10) showed a slight decline in the L^* values (Table 3). In contrast, FGM-20 showed a slight increase. However, these fluctuations were not significant ($p > 0.05$) and there were no significant differences among treatments/beverage types at each time point during the storage (1, 7, 14, and 21d). Decreasing L^* values over the refrigerated storage (15 d) of dried white sapote fruit (*Casimiroa edulis*) incorporated bio-low fat goat milk yoghurt drink was previously reported by Elkot et al. (2023).

The redness of the bael-incorporated products (FGM-5, -10, and -20) remained significantly higher ($p < 0.05$) than the product without bael (FGM-0) throughout the storage. Excepting the product without bael (FGM-0), the a^* value in all bael-incorporated fermented goat milk beverages was increased with advancing storage time making complete shifts from green to red by 21 days of storage (Table 3). However, these increases were not significant ($p > 0.05$) in FGM-10 and −20. Whereas, it was significant in FGM-5. This observation suggests that there is a possible accumulation of red pigments over the advancing storage period. Usually red colour indicates the presence of flavonoids. Previous research reported that the flavonoid content in the bael fruit pulp is approximately 15 mg g^{-1} on a dry matter basis (Charoensiddhi & Anprung, 2008). Based on these facts it can be concluded that the liberation of red coloured pigment from the bael fruit pulp may be responsible for the increased redness. Increasing redness has also been reported by Machado et al. (2017) in sting bee honey-added goat milk yoghurt over refrigerated storage.

The yellowness ($+b^*$ values) in all beverage types considerably increased by day-7 of the storage and then declined until day-21. However, this decline was only significant ($p < 0.05$) in FGM-20. Except for FGM-20, the yellowness in all other beverage types (FGM-0, −5, and −10) was higher compared to day-1. This may be due to the accumulation of liberated yellow-coloured components such as carotenoids and xanthophyll from the bael fruit matrix during post-fermentation. It can also be due to non-enzymatic browning (Maillard reactions) taking place during storage (Costa et al., 2022). The continuous decline in yellowness observed after 7 days of storage may be due to the simultaneous degradation of yellow-coloured compounds such as riboflavin, beta-carotene, and vitamin-A molecules as previously reported by Popov-Raljić et al. (2008) for UHT milk over refrigerated storage. Antioxidant activities of certain molecules may also be responsible for the decreasing yellowness over the storage (Costa et al., 2022). Decreasing yellowness over the storage has also been reported by Araújo et al. (2022) in a lactose-free probiotic goat milk beverage incorporated with red jumbo pulp and by Costa et al. (2022) in a cupuassu-added goat milk yoghurt. Despite the decline in yellowness over the storage, the yellowness in all bael-incorporated beverages (FGM-5, −10, and −10) was significantly higher ($p < 0.05$) than that of the control (FGM-0) after 14 days of storage. Further, this hike in yellowness was proportionated with the level of bael incorporated suggesting that yellowness is mainly resulting from the compounds originating from bael most probably carotenoids that were reported to present at a quantity of about 32 μg/g of dry weight basis (Charoensiddhi & Anprung, 2008).

Compared to the control (FGM-0), the C^* value (chroma) of bael-incorporated beverages remained higher throughout the storage proportionately to the level of bael incorporated. Among these, the beverages with incorporation levels of 10 % and 20 % showed significantly higher ($p < 0.05$) C^* values from day 1 of the storage, whereas the beverage with 5 % incorporation level showed significantly higher C^* values from day 7. The C^* values over the storage showed a similar pattern as that of the b^* values where the values initially increased on

day 7 and gradually decreased thereafter. This can be expected as there was a strong positive correlation between b^* and C^* values throughout the storage (Table 4). The hue (h^*) value of the control (FGM-0) was significantly higher ($p < 0.05$) than the bael-incorporated beverages. All beverage types including the control experienced a decline in h^* value over the storage. However, the decline in the control (FGM-0) and 5 % bael-incorporated beverage (FGM-5) was only significant ($p < 0.05$). The control showed the highest whiteness index among the treatments throughout the storage. Although there were fluctuations in the whiteness index of all beverage types, there was no significant difference ($p > 0.05$) between the values on day 1 and day 21. There was a strong positive correlation between the whiteness index and the L^* value throughout the storage. The overall colour change (ΔE^*) among the treatments and its variation throughout the storage period varied in different magnitudes. However, those variations among the treatments as well as among different time points throughout the storage were not significant ($p > 0.05$). The absence of any significant overall colour change has also been reported by Ma et al. (2022) during the storage of blue honeysuckle juice-incorporated fermented goat milk. The statistical analysis of our study showed that neither the treatment/beverage type nor storage time had a significant influence on the overall colour change. A significant interaction effect of treatment × storage time existed ($p = 0.022$).

3.4. Probiotic viability

Viable counts of *Lacticaseibacillus rhamnosus* GG (LGG) in the fermented goat milk beverages were counted at 1, 7, 14, and 21 days of refrigerated storage and depicted in Fig. 2. Results from mixed ANOVA revealed that both the treatment and storage time had a significant influence on the probiotic counts ($p < 0.05$). In addition, storage time and treatment interaction were also found to be significant ($p < 0.05$). On days 1 and 7, the viability of LGG in all products remained just below 10^8 CFU/mL or higher. Thereafter (on 14 and 21 days), the viable counts of LGG remained significantly higher ($p < 0.05$) only in bael-incorporated fermented beverages (FGM-5, -10, and -20). There were no significant differences in LGG counts among bael-incorporated beverage types (FGM-5, -10, and -20) after 14 d of storage. In addition, the Pearson correlation analysis revealed that there was a strong positive correlation between the LGG viability, and b^* and a^* values. This correlation was much more prominent at 14 and 21 days of storage ($r > 0.73$). These two results combined suggest that bael fruit pulp contains some materials that promote probiotic viability in an acidic environment over refrigerated storage. This may be due to two major reasons. First is that bael fruit pulp contains a considerably higher content of total carbohydrates that include both the soluble and non-soluble fractions. The soluble fraction (N-free extract) represents soluble carbohydrates such as sugars and starch which may provide additional fermentable substrates for probiotic growth, metabolism, and survival during storage. The total carbohydrate and total sugar contents in bael fruit pulp vary between 31–42 % and 12–20 %, respectively (Roy et al., 2011; Sarkar et al., 2020; Sharma et al., 2022). In our study too, the soluble carbohydrate content (N-free extract) in bael was 27.4 ± 0.25% suggesting that these carbohydrates may have a great potential to be a reason for the higher LGG counts observed in bael-incorporated beverages. Secondly, polyphenols were reported to improve the growth and viability of probiotics in milk (de Azevedo et al., 2018) while acting as hydrogen peroxide scavengers and protecting probiotics during fermentation and storage (Chait et al., 2020). Since bael fruit pulp contains considerable amounts of polyphenols (87.34 mg g^{-1} of dw) including flavonoids (15 mg g^{-1} of dw) and carotenoids (33 μg/g of dw) (Charoensiddhi & Anprung, 2008), and as these compounds have a direct influence on a^* and b^* values, the link between the above polyphenolic compounds and the LGG viability cannot be eliminated. In addition, the antioxidative effect exerted by ascorbic acid in the bael fruit pulp itself may also have a protective effect on probiotics. Other than flavonoids and carotenoids, phenolic acids such as tannic acid (2.81 ± 4.8 g/100 g), gallic acid (873.6 μg/g), marmelosin (415 - 737 μg/g), ellagic acid (248.5 μg/g), chlorogenic acid (136.8 μg/g), and ferulic acid (96.3 μg/g) are also present in relatively higher concentrations in the bael fruit pulp that may be responsible for the increased LGG viability in bael incorporated beverages (Sharma et al., 2022). More research should be done to investigate the relationships between bael polyphenols and probiotic viability as well as their mechanisms of action. The antioxidative effect of bael fruit pulp has been highlighted in previous research (Charoensiddhi & Anprung, 2008).

Our study is compatible with the previous research findings where the incorporation of certain plant-derived additives significantly increased probiotic viability over storage. For instance, Machado et al. (2017) reported that *Lactobacillus acidophilus* counts significantly increased in honey-incorporated goat milk yoghurt over 28 days of storage. Viable counts of *Bifidobacterium bifidum* DSMZ and *Lactobacillus helveticus* CH5 have been reported to significantly increase upon the addition of carob molasses into fermented goat milk over 14 days of storage (El-Sayed et al., 2024). The incorporation of bael fruit pulp was also reported to significantly increase LGG counts in buffalo milk yoghurt over 21 d of refrigerated storage (Yapa et al., 2023).

Results of the current study showed that there was a continuous decline in LGG viable counts throughout the storage. The viable counts on day one were 8.05–8.29 log CFU/mL which fell to 7.94–8.40 by day 7, to 6.70–7.45 log CFU/mL by day 14, and to 6.08–7.09 log CFU/mL by day 21. This decline was more drastic in the product without bael (FGM-

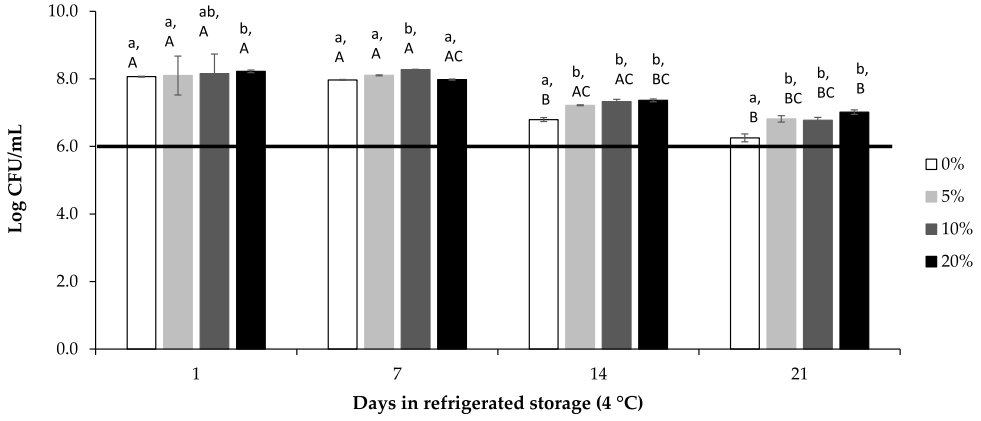

Fig. 2. Viable counts of LGG of fermented goat milk formulations during 21 d of refrigerated storage (4 °C). Results are mean ± SD. [ab]Means without common superscripts in a particular time point are different ($p < 0.05$). [ABC]Means without common superscripts between time points of a particular treatment are different ($p < 0.05$).

0) which showed a significant decline just after 14 days of storage leading to an overall decline of 1.82 folds after 21 days compared to 1.21–1.38 folds (24–33 % lower decline) in bael-incorporated beverages. Most probably, the reason for this decline may be the limitation of fermentable or growth-promoting substances in the control. In bael-incorporated beverages, this could not be an issue since bael provides extra fermentable substrates such as sugars and other carbohydrates that favour enhanced probiotic survivability during storage. The competition for substrate, the antagonistic effect between the probiotic strains and conventional starter cultures, and the synthesis of bacteriocins and organic acids are among the other reasons that may suppress the probiotic survivability during storage (de Morais et al., 2022). Declining viable counts of the probiotics during refrigerated storage is a common phenomenon reported by many authors regardless of the dairy product or type of milk used to prepare the respective dairy product. For instance, significantly decreasing *Bifidobacterium animalis* ssp. *lactis* and *B. longum* AD-50 counts were reported in monofermented goat milk beverages after 14 days of storage (Mituniewicz-malek et al., 2017). A significant decrease in viable *Limolactobacillus mucosae* counts (from 9.53 to 8.96 log CFU/mL) was reported in probiotic goat milk yoghurt during 28d of storage (de Morais et al., 2022) and for *Lactobacillus acidophilus* La-05 in honey incorporated goat milk yoghurt (Machado et al., 2017).

Although a declining trend in probiotic counts was observed in the current study, the viable counts were maintained well above 10^6 CFU/mL throughout the 21 days of storage. It is generally accepted that at least 10^6 to 10^7 CFU/ mL of viable probiotics must be present in a food material at the time of consumption to exert any health effect on the host. This confirms that the beverages provide more than the daily recommended dose of probiotics even after 21 days of storage. The current study confirmed that fermented goat milk beverage is an ideal matrix to deliver the EPS-producing probiotic LGG in sufficient quantities. This may be attributed to the beneficial properties of goat milk matrix such as appropriate pH, good buffering capacity, and high nutrient content (Ranadheera et al., 2018). Previous research findings also revealed that goat milk is an ideal matrix to preserve therapeutic doses of *Bifidobacterium* strains such as *Bifidobacterium animalis* ssp. *lactis* Bb-12 (Madhubasani et al., 2020; Mituniewicz-malek et al., 2017), *B. bifidum* Bb-11 (Elkot et al., 2023), *B. animalis* ssp. *lactis* AD 600 (Mituniewicz-malek et al., 2017), *B. longum* AD-50 (Mituniewicz-malek et al., 2017), *B. animalis* ssp. *lactis* Probio M8 (Guo et al., 2022), *B. bifidum* DSMZ (El-Sayed et al., 2024), and *Lactobacillus* strains such as *Lactobacillus helveticus* CH5 (El-Sayed et al., 2024), *L. acidophilus* La-05 (Elkot et al., 2023; Machado et al., 2017), and *Limosilactobacillus mucosae* (de Morais et al., 2022), and *Lacticaseibacillus paracasei* (Araújo et al., 2022). Out of the three bael concentrations tested in the current study, the product containing 20 % bael produced the highest LGG viability after 21 days. In a previous study however, Yapa et al. (2023) reported that bael concentrations higher than 5 % showed detrimental effects on the LGG viability in buffalo milk yoghurt although it maintained the viability of $>10^7$ CFU/mL after 21 days of storage. However, in the current study, there was no bael concentration-dependent effect on LGG viability as all three incorporation levels of bael resulted in almost the same LGG viability. This may be attributed to the higher buffering capacities of goat milk compared to buffalo milk.

In summary, the current study found that adding bael fruit pulp to fermented goat milk beverage significantly alters its color, buffers post-acidification during storage, and maintains viable probiotic LGG counts at significantly higher levels compared to the beverage without bael. However, the study lacks sensory analysis to determine the sensory acceptance of the products. Previous studies have shown that adding bael fruit pulp to ice cream, soup, sherbet, and bread significantly increases mean sensory scores for colour and overall acceptability (Begum et al., 2024; Chaudhary et al., 2023). These findings suggest that bael could significantly impact the sensory attributes of the food product in a positive way. Thus, future research should investigate consumer acceptability of the beverage formulations tested. Functional foods offer additional health benefits beyond traditional nutrition, and incorporating bael and probiotic LGG into fermented goat milk can provide consumers with a wide range of well-proven health benefits from a single product. This research may provide valuable insights into the development of novel dairy-based functional beverages using bael and LGG.

4. Conclusions

In conclusion, this study confirmed that probiotic *Lacticaseibacillus rhamnosus* GG (LGG) grows better in goat milk when bael fruit pulp is incorporated pre-fermentation, maintaining significantly higher probiotic counts than that in fermented goat milk without bael, in particular 14–21 days of the refrigerated storage. Bael fruit pulp also boosts the nutritional composition and acidification abilities of the starter cultures while significantly affecting the colour characteristics, pH, and LGG viability. Bael may also positively affect the organoleptic properties of fermented goat milk in particular the colour, texture, and overall acceptability leading to improved consumer preference for value-added goat milk products. This novel bael-goat milk probiotic beverage may deliver all the goodness associated with probiotics, bael, and goat milk in a single product. The developed bio-fermented goat milk is considered a novel functional dairy beverage for those with cow milk intolerances and those searching for healthy foods with a large array of health-promoting effects. It will also diversify the utilization of bael which has a long history in traditional medicine in certain parts of the world.

Funding

This research received no external funding.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

Data availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

CRediT authorship contribution statement

Jithmi Siriwardhana: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **D.M.D. Rasika:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Dinusha Yapa:** Writing – review & editing, Investigation, Formal analysis. **W.A.D.V. Weerathilake:** Writing – review & editing, Validation, Resources. **Hasitha Priyashantha:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors acknowledge Wayamba University of Sri Lanka for providing the necessary laboratory facilities, and equipment for this study. The authors are thankful to Dr J.M.K.J.K. Premarathna for providing LMS Lactobacillus media and anaerobic sachets for the research work. Assistant provided by all the Heads and laboratory staff of the Department of Livestock & Avian Sciences (Mr Nalaka Sandaruwan, Mrs. Wajira Ginigaddara, Mr Ajantha Kumara, and Mr Dharmasiri), Dept. of Aquaculture and Fisheries, and Dept. of Food Science & Technology are highly appreciated.

References

AOAC. (2012). *Official methods of analysis of AOAC international* (19th Ed.). Maryland, USA: AOAC International.

Araújo, N. G., Barbosa, I. M., Lima, T. L. S., Moreira, R. T., & Cardarelli, H. R. (2022). Development and characterization of lactose-free probiotic goat milk beverage with bioactive rich jambo pulp. *Journal of Food Science and Technology, 59*(10), 3806–3818.

Begum, N. J., Chandimala, U. R., Hettiarachchi, H. A. P., & Gimhani, J. A. N. (2024). Development of functional ice cream by incorporating bael fruit (*Aegle marmelos*) pulp and evaluation of its quality parameters. *Sri Lankan Journal of Technology Research*, 29–35.

Bruzantin, F. P., Daniel, J. L. P., Da Silva, P. P. M., & Spoto, M. H. F. (2016). Physicochemical and sensory characteristics of fat-free goat milk yogurt with added stabilizers and skim milk powder fortification. *Journal of Dairy Science, 99*(5), 3316–3324. https://doi.org/10.3168/jds.2015-10327

Chait, Y. A., Gunenc, A., Bendali, F., & Hosseinian, F. (2020). Simulated gastrointestinal digestion and *in vitro* colonic fermentation of carob polyphenols: Bioaccessibility and bioactivity. *Lwt, 117*, Article 108623. https://doi.org/10.1016/j.lwt.2019.108623

Charoensiddhi, S., & Anprung, P. (2008). Bioactive compounds and volatile compounds of Thai bael fruit (*Aegle marmelos* (L.) Correa) as a valuable source for functional food ingredients. *International food Research journal, 15*(3), 287–295.

Chaudhary, V., Kumar, V., Sharma, H. P., Singh, V. K., Vaishali, A. S. P., & Sunil, A. M. A. (2023). Development of value added products prepared from bael (*Aegle marmelos* L.) powder and its quality evaluation. *The Pharma Innovation Journal, 12*(5), 1111–1117.

Cheng, N., Barbano, D. M., & Drake, M. (2019). Effects of milk fat, casein, and serum protein concentrations on sensory properties of milk-based beverages. *Journal of dairy science, 102*(10), 8670–8690. https://doi.org/10.3168/jds.2018-16179

CIE 11664-4:2019; Available online Colorimetry — Part 4: CIE 1976 L*a*b* colour space | CIE. isO: Geneva, Switzerland; Commission Internationale deL'éclairage: Vienna, Austria, 2019.

Costa, M. P., Frasao, B. S., Silva, A. C. O., Freitas, M. Q., Franco, R. M., & Conte-Junior, C. A. (2015). Cupuassu (*Theobroma grandiflorum*) pulp, probiotic, and prebiotic: Influence on color, apparent viscosity, and texture of goat milk yogurts. *Journal of Dairy Science, 98*(9), 5995–6003. https://doi.org/10.3168/jds.2015-9738

Costa, M. P., Rosario, A. I. L., Silva, V. L., Vieira, C. P., & Conte-Junior, C. A. (2022). Rheological, physical and sensory evaluation of low-fat cupuassu goat milk yogurts supplemented with fat replacer. *Food Science of Animal Resources, 42*(2), 210. https://doi.org/10.5851/kosfa.2021.e64

da Silva Dantas, D. L., Viera, V. B., Soares, J. K. B., dos Santos, K. M. O., do Egito, A. S., de Figueirêdo, R. M. F., et al. (2022). *Pilosocereus gounellei* (xique-xique) flour: Improving the nutritional, bioactive, and technological properties of probiotic goat-milk yogurt. *LWT, 158*, Article 113165. https://doi.org/10.1016/j.lwt.2022.113165

de Azevedo, P. O. D. S., Aliakbarian, B., Casazza, A. A., LeBlanc, J. G., Perego, P., & de Souza Oliveira, R. P. (2018). Production of fermented skim milk supplemented with different grape pomace extracts: Effect on viability and acidification performance of probiotic cultures. *PharmaNutrition, 6*(2), 64–68. https://doi.org/10.1016/j.phanu.2018.03.001

de Morais, J. L., Garcia, E. F., Viera, V. B., Pontes, E. D. S., de Araújo, M. G. G., de Figueirêdo, R. M. F., et al. (2022). Autochthonous adjunct culture of *Limosilactobacillus mucosae* CNPC007 improved the techno-functional, physicochemical, and sensory properties of goat milk Greek-style yogurt. *Journal of Dairy Science, 105*(3), 1889–1899. https://doi.org/10.3168/jds.2021-21110

Eissa, E. A., Ahmed, I. M., Yagoub, A. E. A., & Babiker, E. E. (2010). Physicochemical, microbiological and sensory characteristics of yoghurt produced from goat milk. *Livestock Research for Rural Development, 22*(8), 247–253.

Elkot, W. F., Talaat, H., Abdeldaiem, A. M., Alnuzaili, E. S., Eljeam, H. A. A., Ammar, A. F., et al. (2023). Effect of using dried white sapote fruit (*Casimiroa edulis*) on the quality characteristics of bio-low-fat goat milk yoghurt drink. *Saudi Journal of Biological Sciences, 30*(12), Article 103844. https://doi.org/10.1016/j.sjbs.2023.103844

El-Sayed, M. I., Aly, E., & El-Deeb, A. M. (2024). Improving the physicochemical and antioxidative properties of fermented goat milk using carob molasses and some probiotic strains. *Food Science and Biotechnology, 33*(3), 657–666. https://doi.org/10.1007/s10068-023-01382-2

Fine, J. (1932). The iodimetric method of determining lactose in milk. *Biochemical Journal, 26*(3), 569. https://doi.org/10.1042/bj0260569

Guo, S., Chen, M., Wu, T., Liu, K., Zhang, H., & Wang, J. (2022). Probiotic *Bifidobacterium animalis* ssp. *lactis* Probio-M8 improves the properties and organic acid metabolism of fermented goat milk. *Journal of Dairy Science, 105*(12), 9426–9438. https://doi.org/10.3168/jds.2022-22003

Hill, C., Guarner, F., Reid, G., Gibson, G. R., Merenstein, D. J., Pot, B., et al. (2014). The International Scientific Association for Probiotics and Prebiotics consensus statement on the scope and appropriate use of the term probiotic. *Nature Reviews Gastroenterology & Hepatology, 11*(8), 506–514.

Kavas, G., Uysal, H., Kihc, S., Akbulut, N., & Kesenkas, H. (2003). Some properties of yoghurts produced from goat milk and cow-goat milk mixtures by different fortification methods. *Pakistan Journal of Biological Sciences, 6*(23), 1936–1939 (Pakistan).

Kumperscak, H. G., Gricar, A., Ülen, I., & Micetic-Turk, D. (2020). A pilot randomized control trial with the probiotic strain *Lactobacillus rhamnosus* GG (LGG) in ADHD: Children and adolescents report better health-related quality of life. *Frontiers in Psychiatry, 11*, Article 520852. https://doi.org/10.3389/fpsyt.2020.00181

Ma, J., Miao, Y., Li, J., Ma, Y., Wu, M., Wang, W., et al. (2022). Incorporation of blue honeysuckle juice into fermented goat milk: Physicochemical, sensory and antioxidant characteristics and *in vitro* gastrointestinal digestion. *Foods, 11*(19), 3065. https://doi.org/10.3390/foods11193065

Machado, T. A. D. G., de Oliveira, M. E. G., Campos, M. I. F., de Assis, P. O. A., de Souza, E. L., Madruga, M. S., et al. (2017). Impact of honey on quality characteristics of goat yogurt containing probiotic *Lactobacillus acidophilus*. *LWT, 80*, 221–229. https://doi.org/10.1016/j.lwt.2017.02.013

Madhubasani, G. B. L., Prasanna, P. H. P., Chandrasekara, A., Gunasekara, D. C. S., Senadeera, P., Chandramali, D. V. P., et al. (2020). Exopolysaccharide producing starter cultures positively influence on microbiological, physicochemical, and sensory properties of probiotic goats' milk set-yoghurt. *Journal of Food Processing and Preservation, 44*(3), e14361. https://doi.org/10.1111/jfpp.14361

Mituniewicz-Małek, A., Ziarno, M., Dmytrów, I., & Balejko, J. (2017). Effect of the addition of Bifidobacterium monocultures on the physical, chemical, and sensory characteristics of fermented goat milk. *Journal of Dairy Science, 100*(9), 6972–6979. https://doi.org/10.3168/jds.2017-12818

Pappa, E. C., Kondyli, E., Bosnea, L., Malamou, E., & Vlachou, A. M. (2022). Chemical, microbiological, sensory, and rheological properties of fresh goat milk cheese made by different starter cultures during storage. *Journal of Food Process Engineering, 45*(7), e13788. https://doi.org/10.1111/jfpe.13788

Popov-Raljić, J. V., Lakić, N. S., Laličić-Petronijević, J. G., Barać, M. B., & Sikimić, V. M. (2008). Color changes of UHT milk during storage. *Sensors, 8*(9), 5961–5974. https://doi.org/10.3390/s8095961

Ram, D., & Singh, I. S. (2003). Physico-chemical studies on beal (*Aegle marmelos* Correa) fruits. *Progressive Horticulture, 35*, 199–201.

Ranadheera, C. S., Naumovski, N., & Ajlouni, S. (2018). Non-bovine milk products as emerging probiotic carriers: Recent developments and innovations. *Current Opinion in Food Science, 22*, 109–114. https://doi.org/10.1016/j.cofs.2018.02.010

Roy, S. K., Saran, S., & Kitinoja, L. (2011). Bael (*Aegle marmelos* (L.) Corr. Serr.). Vol. 1. M.Y. Elhadi MY. *Postharvest biology and technology of tropical and subtropical fruits* (pp. 186–216). London, UK: Academic Press.

Salva, S., Tiscornia, I., Gutiérrez, F., Alvarez, S., & Bollati-Fogolín, M. (2021). *Lactobacillus rhamnosus* postbiotic-induced immunomodulation as safer alternative to the use of live bacteria. *Cytokine, 146*, Article 155631. https://doi.org/10.1016/j.cyto.2021.155631

Sanborn, V. E., Azcarate-Peril, M. A., & Gunstad, J. (2020a). *Lactobacillus rhamnosus* GG and HbA1c in middle age and older adults without type 2 diabetes mellitus: A preliminary randomized study. *Diabetes & Metabolic Syndrome: Clinical Research & Reviews, 14*(5), 907–909. https://doi.org/10.1016/j.dsx.2020.05.034

Sanborn, V., Azcarate-Peril, M. A., Updegraff, J., Manderino, L., & Gunstad, J. (2020b). Randomized clinical trial examining the impact of *Lactobacillus rhamnosus* GG probiotic supplementation on cognitive functioning in middle-aged and older adults. *Neuropsychiatric Disease and Treatment*, 2765–2777. https://doi.org/10.2147/NDT.S270035

Sarkar, T., Salauddin, M., & Chakraborty, R. (2020). In-depth pharmacological and nutritional properties of bael (*Aegle marmelos*): A critical review. *Journal of Agriculture and Food Research, 2*, Article 100081. https://doi.org/10.1016/j.jafr.2020.100081

Sharma, H., Singh, A. K., Rao, P. S., Deshwal, G. K., Singh, R., & Kumar, M. D. (2024). A study on incorporation of giloy (*Tinospora cordifolia*) for the development of shelf-stable goat milk based functional beverage. *Journal of Food Science and Technology, 61*(3), 503–515. https://doi.org/10.1007/s13197-023-05858-1

Sharma, N., Kumar, M., Radha, Zhang, B., Kumari, N., Singh, D., Chandran, D., Sarkar, T., Dhumal, S., Sheri, V., Day, A., Rajalingam, S., Viswanathan, S., Mohankumar, P., Vishvanathan, M., Sathyaseelan, S. K., & Lorenzo, J. M (2022). *Aegle marmelos* (L.) correa: An underutilized fruit with high nutraceutical values: A review. *International Journal of Molecular Sciences, 23*(18), 10889. https://doi.org/10.3390/ijms231810889

Wang, H., Wang, C. N., & Guo, M. R. (2019). Effects of addition of strawberry juice pre-or postfermentation on physiochemical and sensory properties of fermented goat milk.

Journal of Dairy Science, 102(6), 4978–4988. https://doi.org/10.3168/jds.2018-15750

Wang, W., Bao, Y., Hendricks, G. M., & Guo, M. (2012). Consistency, microstructure and probiotic survivability of goats' milk yoghurt using polymerized whey protein as a co-thickening agent. *International Dairy Journal, 24*(2), 113–119. https://doi.org/10.1016/j.idairyj.2011.09.007

Yapa, D., Rasika, D. M. D., Weerathilake, W. A. D. V., Siriwardhana, J., & Priyashantha, H. (2023). Effects of fermenting with *Lacticaseibacillus rhamnosus* GG on quality attributes and storage stability of buffalo milk yogurt incorporated with bael (*Aegle marmelos*) fruit pulp. *NFS Journal, 31*, 102–109. https://doi.org/10.1016/j.nfs.2023.04.002