Optimization and quality evaluation of low-fat goat milk Lollies using response surface methodology

R. Sindhav*, K.K. Ahuja, T. Hazra, A. Bihola

College of Dairy Science, Kamdhenu University, Amreli, Gujarat, India
*Corresponding Author e-mail: rohitsindhav7@gmail.com

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Abstract

Goat milk possesses unique compositional and functional characteristics, including smaller fat globules and a higher proportion of short- and medium-chain fatty acids, which contribute to improved digestibility and potential health benefits. Despite these advantages, its utilization in value-added frozen dairy products remains limited, particularly in standardized low-fat formulations. Therefore, the present study aimed to develop and optimize a low-fat goat milk lolly using Response Surface Methodology and to evaluate the effects of milk fat and sweetener levels on sensory, physicochemical, colour, antioxidant, and microbiological attributes of the product. Optimization of the formulation was carried out using a Central Composite Rotatable Design with milk fat (0.5–2.0%) and sweetener level (15–25%) as independent variables. Goat milk lollies were prepared using standardized processing conditions, including pasteurization (80 °C for 5 min), controlled freezing, and hardening. The findings revealed that both milk fat and sweetener levels considerably influenced sensory and physicochemical characteristics of goat milk lollies. Increasing milk fat improved body and texture, melting resistance, and overall acceptability, whereas sweetener concentration notably affected sweetness perception, mix viscosity, and freezing behaviour. The optimized formulation produced goat milk lollies with high sensory acceptability, desirable melting characteristics, improved mix viscosity, favourable colour attributes, and antioxidant activity. Microbiological counts of optimized samples remained within permissible limits, indicating effective thermal processing. The findings demonstrate the feasibility of developing a low-fat goat milk-based frozen confection with acceptable sensory quality, functional attributes, and microbiological safety, highlighting the potential of goat milk for diversification into value-added frozen dairy products.

Keywords: Goat milk; Milk lolly; Low-fat frozen confection; Response surface methodology; Optimization; Sensory quality

Introduction

Milk and milk-based products constitute an essential component of human nutrition due to their balanced composition of proteins, lipids, carbohydrates, minerals and vitamins. Globally, milk production has expanded steadily in response to population growth, urbanization, and evolving dietary patterns. According to the Food and Agriculture Organization (FAO), global milk production currently exceeds 930 million tonnes annually, with the majority derived from bovine species, particularly cows and buffaloes (FAO, 2024; OECD/FAO, 2025). Nevertheless, milk from small ruminants such as goats and sheep represents a significant and increasingly important segment of the global dairy sector, accounting for approximately 17–18% of total milk production (Ranadheera et al., 2018; Meza-Herrera et al., 2024). Among these species, goats contribute substantially to global milk output, producing more than 20 million tonnes annually, and play a crucial role in supporting the livelihoods and nutritional security of rural communities, particularly in Asia, Africa, and Mediterranean regions where goats are well adapted to marginal environments and semi-arid climatic conditions (Navarrete-Molina et al., 2024; Singh et al., 2023; Idamokoro, 2023, Singh et al., 2025).

Goat milk possesses several unique compositional and functional characteristics that distinguish it from bovine milk and contribute to its nutritional value. The fat globules in goat milk are generally smaller and more uniformly distributed than those in cow milk, which may influence lipid digestion and the textural characteristics of dairy products (Clark & Mora García, 2017; Silanikove et al., 2010). Moreover, goat milk contains relatively higher proportions of short- and medium-chain fatty acids such as caproic (C6:0), caprylic (C8:0), and capric (C10:0), which are rapidly metabolized and serve as readily available sources of energy (Raynal-Ljutovac et al., 2008; Nayik et al., 2021). These fatty acids contribute to the distinctive lipid composition and sensory characteristics of goat milk. In addition, the protein composition of goat milk differs from that of cow milk, particularly in terms of reduced levels of αs1-casein, which may influence protein digestion and processing characteristics (Clark & Mora García, 2017; Koloskova et al., 2021; AlKaisy et al., 2023). Goat milk is also recognized as a rich source of essential minerals, including calcium, phosphorus, magnesium, and potassium, and contains several bioactive compounds such as peptides, oligosaccharides, and antioxidant components that contribute to its nutritional characteristics (Nayik et al., 2022; Thakur et al., 2024; Mishra et al., 2026).

Despite these nutritional advantages, the commercial utilization of goat milk remains relatively limited compared with cow milk. In many developing countries, including India, goat milk is predominantly consumed as fluid milk or processed into a narrow range of traditional dairy products such as fermented milk products and artisanal cheeses (Akshit et al., 2023; Mishra et al., 2025). The limited diversification of goat milk products restricts their market potential and economic value. Concurrently, consumer demand for innovative, nutritious, and sensory-acceptable dairy products is increasing due to growing awareness of health, digestive well-being, and functional foods (Nayik et al., 2021; Idamokoro, 2023). This evolving consumer preference highlights the necessity for developing novel value-added dairy products derived from goat milk, which could enhance product diversification and generate new market opportunities for both producers and the dairy processing industry.

Frozen dairy products represent one of the most rapidly expanding segments of the global dairy market due to their wide consumer acceptance, appealing sensory characteristics, and considerable potential for product innovation. Products such as ice cream, frozen yogurt, and milk-based frozen desserts are widely consumed across all age groups (Goff, 2015; Wu et al., 2025). However, the majority of commercially available frozen dairy products are formulated using cow milk and often contain relatively high fat levels. In recent years, increasing attention has been directed towards the development of low-fat and alternative frozen dairy formulations that provide reduced fat content while maintaining desirable sensory attributes (Tang et al., 2025; Chang et al., 2025). In this context, milk lollies represent a simple frozen dairy confection prepared by freezing sweetened milk mixtures in moulds without significant aeration. These products are particularly popular in tropical and subtropical regions due to their refreshing taste, simple manufacturing process, and low production cost.

The application of goat milk in frozen dairy products presents both opportunities and technological challenges. The characteristic flavour of goat milk, often described as “goaty,” may influence consumer acceptance if not appropriately balanced through formulation adjustments (Silanikove et al., 2010; Akshit et al., 2023). Additionally, differences in the total solids, protein and fat composition of goat milk can influence viscosity, freezing behaviour, and structural stability of frozen desserts (Clark & Mora García, 2017; Mahmoudi et al., 2025). Therefore, optimization of formulation parameters is essential to achieve desirable product quality and consumer acceptability. Response Surface Methodology (RSM) has emerged as an effective statistical approach for optimizing food formulations by evaluating the interactive effects of multiple variables and identifying optimal formulation conditions with minimal experimental trials (Chaudhary et al., 2025).

Although several studies have explored the utilization of goat milk in fermented dairy products, cheeses, and beverages, scientific information regarding the development and optimization of goat milk-based frozen confections remains limited (Salinas-González et al., 2025; Mishra et al., 2026). In particular, there is a scarcity of research focusing on low-fat frozen dairy products derived from goat milk and the influence of formulation variables on their

sensory, physicochemical, and quality characteristics. Consequently, the development of optimized goat milk-based frozen dairy products such as milk lollies is important from both technological and commercial perspectives.

The development of goat milk lollies offers several advantages. First, it provides a novel avenue for value addition of goat milk, thereby supporting the diversification of dairy product portfolios. Second, it enables the formulation of low-fat frozen dairy products while maintaining acceptable sensory quality. Third, it creates potential market opportunities in regions with high goat milk production where conventional dairy processing infrastructure may be limited. Furthermore, such products may appeal to consumers seeking alternative dairy foods with desirable sensory characteristics and convenient consumption, thereby contributing to the expansion of the global goat milk product market. In the present study, synthetic yellow colour and artificial mango flavour were incorporated to improve product appearance and flavour acceptability. The use of natural colourants and flavouring agents may be explored in future investigations to further improve the formulation.

In view of the above considerations, the present study was undertaken to develop and optimize goat milk-based milk lollies and evaluate the influence of formulation variables on product quality attributes. This study aimed to standardize a low-fat goat milk lolly formulation using RSM. The specific objectives were: (i) to evaluate the effects of milk fat and sweetener levels on sensory attributes of goat milk lollies, including flavour, body and texture, colour and appearance, melting quality and overall acceptability; (ii) to investigate the influence of formulation variables on physicochemical characteristics and colour values of the product; (iii) to determine the antioxidant and microbiological quality of the freshly prepared optimized goat milk lollies; and (iv) to identify the optimal formulation that maximizes sensory acceptability while evaluating the physicochemical and other quality characteristics of the optimized product.

Materials and methods

Fresh goat milk was obtained from healthy lactating goats maintained by local dairy farmers in and around the Amreli district of Gujarat, India. Milk was collected under hygienic conditions using clean, food-grade stainless steel containers. Immediately after milking, the milk was chilled and transported to the Department of Dairy Technology, College of Dairy Science, Kamdhenu University, Amreli, Gujarat, India under refrigerated conditions (≤4 °C) and processed within the same day.

Refined white crystalline cane sugar (sucrose) of food-grade quality, procured from the local market of Amreli, Gujarat, India, was used as the sweetening agent. Carboxymethyl cellulose (CMC) of food-grade purity (Merck Specialities Private Limited, India) was used as a stabilizing agent.

Food-grade synthetic yellow colour and artificial mango flavouring substances (International Flavors and Fragrances, New York, USA) were used to enhance the visual appeal and sensory attributes of the developed goat milk lollies. The concentrations of these additives used in the formulation are specified in the product manufacturing flow diagram (Figure 1). All chemicals, reagents, and microbiological media used for compositional, physicochemical, antioxidant, and microbiological analyses were of analytical reagent (AR) grade and procured from reputed laboratory suppliers.

Experimental Design and Optimization Approach

Optimization of the goat milk lolly formulation was performed using RSM employing a Central Composite Rotatable Design (CCRD). Based on preliminary trials, regulatory considerations, and available scientific literature, two key independent variables known to considerably influence the physicochemical characteristics and sensory attributes of milk-based frozen confections were selected for investigation.

The independent variables studied were- Milk fat content (%) varied from 0.5 to 2.0%, in compliance with the maximum permissible limits prescribed for low-fat frozen dairy products under the Food Safety and Standards Regulations (FSSR, 2011). Sweetener level (%) varied from 15 to 25%, encompassing the functional range required for optimal sweetness perception and textural stability in milk lolly formulations.

The CCRD consisted of a total of thirteen experimental runs, comprising four factorial points (±1, ±1), four axial points (±α, 0; 0, ±α), and five replicated centre points (0, 0). Multiple response variables, such as sensory attributes, physicochemical, and functional properties of goat milk lollies, were selected for optimization.

For each response, a second-order quadratic polynomial model was fitted to describe the relationship between the independent variables and the measured responses, as represented by the following equation:

$$\mathbf{Y=\beta_0+\beta_1A+\beta_2B+\beta_{12}AB+\beta_{11}A^2+\beta_{22}B^2}$$

where Y is the predicted response; β_0 is the intercept; β_1 and β_2 are the linear coefficients; β_{12} represents the interaction effect between milk fat and sweetener levels; and β_{11} and β_{22} are the quadratic coefficients describing curvature effects.

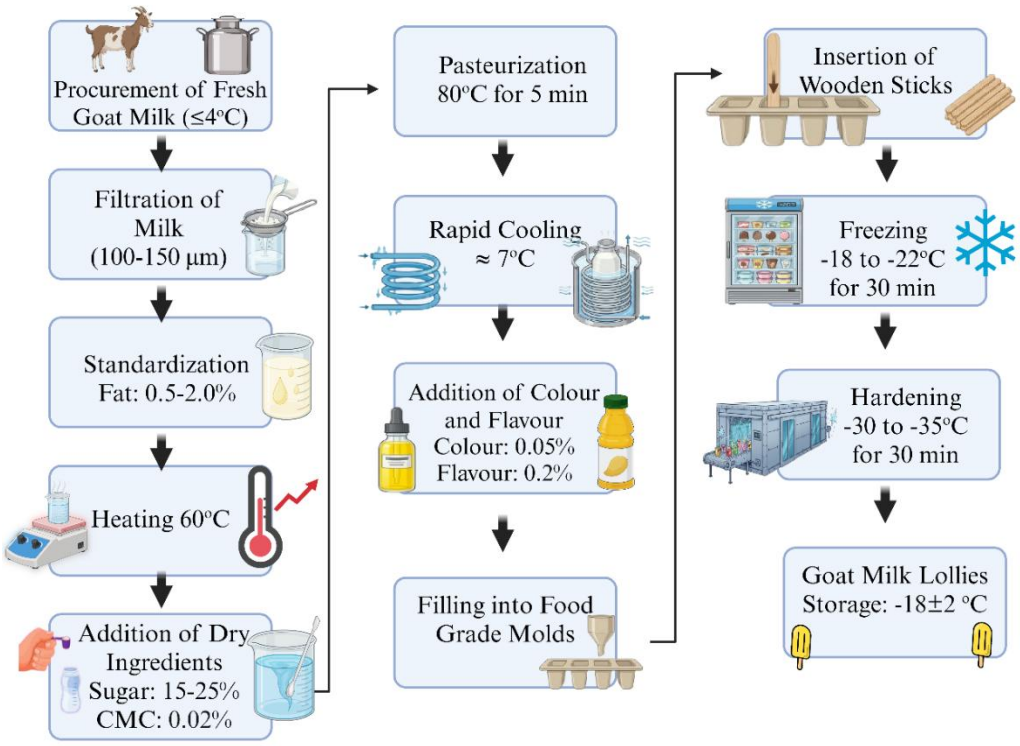


Figure 1 Process flow diagram for the preparation of goat milk lolliesAnalysis of Goat Milk Lollies

Preparation of Goat Milk Lollies

Fresh goat milk was subjected to centrifugal cream separation to obtain skimmed goat milk. The fat content of the milk was subsequently standardized to the required experimental levels by blending the centrifugally separated skimmed goat milk with whole goat milk in appropriate proportions. The standardized milk was then used for the preparation of goat milk lollies according to the experimental formulations. The process

flow diagram for the preparation of goat milk lollies illustrating standardization, thermal processing, ingredient incorporation, freezing, and hardening with key processing parameters, is shown in **Figure 1.**

Compositional Analysis

Compositional analysis of melted goat milk lolly samples was carried out to determine fat, protein, total solids, carbohydrate, and ash contents using standard procedures prescribed by the for ice cream and kulfi products (BIS, 1981; AOAC, 2019). Fat content was determined by the gravimetric method, while protein content was estimated using the Kjeldahl method, applying an appropriate nitrogen-to-protein conversion factor for milk proteins. Total solids were measured by oven drying at a controlled temperature until constant weight, and ash content was determined by incineration in a muffle furnace. Total carbohydrate content was calculated by difference.

Physicochemical Properties

Physicochemical characteristics were evaluated to assess the physical properties and quality attributes of goat milk lollies. Melting rate was determined under controlled ambient temperature conditions to measure resistance to meltdown, which is a key indicator of the melting characteristics of frozen dairy confections (Marshall et al., 2003). Titratable acidity, expressed as percentage lactic acid, and pH were measured to evaluate acid–base balance and potential changes associated with formulation and processing (Marshall et al., 2003).

The viscosity of the milk lolly mix was measured using a controlled-shear rheometer, enabling characterization of flow behaviour and structural development (Marshall et al., 2003; Goff & Hartel, 2013). Viscosity was evaluated as a physicochemical quality parameter and was not included among the sensory responses selected for numerical optimization.

Colour Measurement

Instrumental colour characteristics of the prepared goat milk lolly samples were determined using a HunterLab ColourFlex EZ colorimeter (Hunter Associates Laboratory Inc., Reston, Virginia, USA). The colour parameters were recorded in terms of L* (lightness), a* (red–green coordinate), and b* (yellow–blue coordinate) based

on the CIELAB colour space system. Before measurement, the instrument was calibrated using the manufacturer-supplied standard white calibration tile to ensure accuracy and repeatability of readings.

For colour analysis, the frozen goat milk lolly samples were cut to obtain a uniform and flat surface, and measurements were taken directly on the sample surface. Each sample was evaluated at three different points, and the mean value of the readings was considered for statistical analysis to minimize surface heterogeneity and measurement variability. The L* value represents the degree of lightness or brightness of the sample (ranging from black to white), while the a* value indicates the transition between green (negative values) and red (positive values), and the b* value represents the transition between blue (negative values) and yellow (positive values).

Antioxidant Activity

Antioxidant activity of goat milk lolly samples was determined using the DPPH (2, 2-diphenyl-1-picrylhydrazyl) radical scavenging assay (Brand-Williams et al., 1995; Shahidi & Zhong, 2015). For this assessment, 0.2 g of the sample was added with 3.8 ml ethyl acetate, followed by the addition of 1 ml of the DPPH working solution. This working solution was prepared by diluting 1 ml of stock solution containing 50 mg DPPH in 100 ml of ethyl acetate. After incubation for 10 min, absorbance was measured at 515 nm in UV-Vis spectrophotometer (Shimadzu analytical Pvt. Ltd., Japan; Model: UV-1900i). The control sample consisted of 1 ml of DPPH working solution with 4 ml of ethyl acetate. The percentage of DPPH radical scavenging activity (% RSA) was calculated using an appropriate formula:

$$\% \text{ DPPH RSA} = \frac{\text{Absorbtion of control} - \text{Absorption of sample}}{\text{Absorption of control}} \text{x} 100$$

Sensory Evaluation

Sensory evaluation of the prepared milk lolly samples was carried out using a 9-point hedonic scale to assess sensory acceptability. The samples were evaluated for key sensory attributes, including flavour, colour and appearance, body and texture, melting quality, and overall acceptability. The evaluation was conducted by a panel of 20 trained panellists.

Before the sensory session, panellists were briefed about the evaluation procedure, and written informed consent was obtained from all participants. The samples were coded and served in a randomized order under controlled laboratory conditions to minimize bias. Each sample was presented at a standardized serving temperature to ensure uniformity and reproducibility of sensory responses. Panellists were provided with potable water to rinse their mouths between successive samples to avoid flavour carry-over effects. The 9-point hedonic scale is widely recognized as a reliable and validated method for assessing consumer preference and product acceptability in dairy and food systems (Lawless & Heymann, 2010).

Microbiological Analysis

Microbiological quality of goat milk lolly samples was evaluated by determining total aerobic plate count, yeast and mould count, and coliform count using standard methods (BIS, 1981).

Statistical Analysis

The experimental data generated from the RSM trials were subjected to statistical analysis to evaluate the adequacy and significance of the fitted regression models. Analysis of variance (ANOVA) was performed for each response variable to determine the effects of linear, interaction, and quadratic terms of the independent variables, namely milk fat content and sweetener level. The significance of the model and individual regression coefficients was evaluated using the F-test at a 5% and 1% level of significance. The adequacy of the fitted models was further assessed using the coefficient of determination (R^2), adjusted R^2, and adequate precision values. To compare the mean differences among treatments, Duncan's Multiple Range Test (DMRT) was applied at $p < 0.05$, and treatment means were expressed as mean ± standard error (SE). All statistical analyses were performed using SPSS statistical software (SPSS, version 25.0, IBM Corp., Armonk, NY, USA). Means bearing different superscripts were considered to differ significantly. All statistical analyses and generation of regression equations were carried out using Design-Expert software (Stat-Ease Inc., Minneapolis, USA).

Results and discussions

Effect of Fat and Sweetener Levels on the Sensory Attributes and Flavour score of Goat Milk Lollies

The flavour scores of goat milk lollies were significantly influenced by variations in fat and sweetener levels ($p < 0.05$), as presented in Table 1 and illustrated by the response surface plots (Figure 1a). The flavour scores varied from 6.17 to 8.22 and highest flavour scores were observed near the central region of the experimental design, corresponding to 1.25–1.50 % fat and 20 % sweetener.

The fitted second-order polynomial regression model describing the relationship between formulation variables and flavour score was:

Flavour = 8.16 + 0.1485A + 0.1220B + 0.1325AB − 0.5080A² − 0.9655B²

where A represents fat content and B represents sweetener level.

Regression analysis indicated that fat content exerted a positive and significant linear effect ($p < 0.05$) on flavour score, while its quadratic term was negative and highly significant ($p < 0.01$) (Table 2). The positive linear coefficient suggests that increasing fat concentration initially enhanced flavour perception. Milk fat plays a critical role in flavour development because it acts as a solvent and carrier for hydrophobic volatile flavour compounds, facilitating their retention and controlled release during consumption (Marshall et al., 2003; Goff & Hartel, 2013). In addition, fat contributes to creaminess and lubricity, which improves mouthfeel and enhances the perception of flavour intensity in frozen dairy products (Walstra et al., 2005; Muse & Hartel, 2004). However, the significant negative quadratic effect indicates that excessive fat levels reduced flavour scores beyond the optimum range. Higher fat concentrations may lead to flavour masking and a heavy mouthfeel, which can suppress flavour clarity and ultimately reduce overall sensory acceptability.

Similarly, sweetener concentration exhibited a significant positive linear effect ($p < 0.05$) on flavour score, while its quadratic coefficient was negative and highly significant ($p < 0.01$). Moderate levels of sweetener improved flavour acceptability by balancing the characteristic flavour of goat milk and enhancing the overall sensory profile of the product. Sweetness plays a crucial role in frozen dairy desserts because it modulates taste perception, masks undesirable flavours and improves overall palatability of the product (Marshall et al., 2003; Goff & Hartel, 2013). In addition, sweeteners contribute to the perception of flavour intensity by interacting with other taste components and influencing flavour release during consumption (Lawless & Heymann, 2010). However, excessively high sweetener concentrations resulted in a reduction in flavour scores. Excessive sweetness can lead to taste imbalance and suppress other desirable flavour attributes, thereby reducing overall flavour clarity and consumer acceptability (Hashim & Shamsi, 2016; Carvalho et al., 2022).

The interaction between fat and sweetener (AB) showed a positive coefficient, suggesting a synergistic relationship between these two formulation variables in determining flavour quality. Although the interaction term was statistically non-significant, the three-dimensional response surface plots revealed that simultaneous optimization of fat and sweetener levels within the intermediate range resulted in improved flavour scores.

Effect of Fat and Sweetener Levels on the Body and Texture Score of Goat Milk Lollies

The body and texture scores of goat milk lollies were significantly influenced ($p < 0.05$) by variations in fat and sweetener levels, as presented in Table 1 and illustrated through the response surface plots (Figure 1b). The body and texture scores ranged from 6.17 to 8.33 and the highest scores were recorded near the central region of the experimental design, where fat and sweetener content were kept within an intermediate range.

The fitted second-order polynomial regression model describing the relationship between formulation variables and body and texture score was expressed as:

Body and Texture = 8.16 + 0.3837A + 0.5601B − 0.0700AB − 0.1730A² − 0.6430B²

where A represents fat content (%) and B represents sweetener level (%).

The positive coefficients of the linear terms (A and B) indicate that increasing fat and sweetener levels within the experimental range improved the body and texture characteristics of goat milk lollies. Regression analysis revealed that both fat and sweetener exerted a positive and highly significant linear effect ($p < 0.01$) on body and texture scores, indicating that moderate increases in these components enhanced the structural and sensory attributes of the product (Table 2).

Similarly, increasing sweetener concentration considerably improved body and texture, primarily due to its influence on freezing behaviour and total solids content of the mix. Higher sugar levels increase the concentration of the unfrozen serum phase and depress the freezing point of the system, thereby reducing excessive ice crystal formation and promoting the development of a smooth structure.

The quadratic coefficients of fat (A^2) and sweetener (B^2) were negative, indicating that excessive levels of these components adversely affected textural quality and resulted in a reduction in body and texture scores beyond the optimum range. Similarly, the quadratic effect of sweetener ($p < 0.01$) indicates that excessive sweetener concentrations reduced the body and texture score of the product. Furthermore, the interaction coefficient (AB) was slightly negative, suggesting that simultaneous increases in both variables may marginally reduce the textural quality of the product. Nevertheless, the response surface plots demonstrated that the combined adjustment of fat and sweetener within the intermediate range resulted in improved body and texture scores.

The development of texture in frozen dairy products is strongly governed by microstructural characteristics, including ice crystal size, ice phase volume, air cell distribution, and the rheological properties of the mix. These parameters are directly influenced by formulation variables such as fat and sweetener levels, which regulate freezing dynamics and matrix formation (Goff & Hartel, 2013; Muse & Hartel, 2004). In goat milk lollies, deviations from the optimal range of these components disturbed the equilibrium between the ice phase and the unfrozen serum phase,

Table 1 Effects of fat and sweetener levels on the sensory scores, physico-chemical quality, colour values and viscosity of goat milk lollies

Standard Order	Actual Factors (%)		Coded Values		Responses											
					Sensory Attributes					Physicochemical Properties				Colour Values		
	Fat Content (%)	Sweetener (%)	Fat	Sweetener	Flavour	Body and Texture	Colour and Appearance	Melting Quality	Overall Acceptability	Fat (%)	Total Solids (%)	pH	Viscosity (cP)	L*	a*	b*
1	0.5	15	-1.000	-1.000	6.50	6.28	6.94	6.39	6.17	0.4	20.80	6.56	11.81	80.68	-1.14	62.81
2	2.0	15	1.000	-1.000	6.44	7.17	7.17	7.11	6.50	1.8	22.08	6.60	12.02	79.08	-0.98	61.29
3	0.5	25	-1.000	1.000	6.61	7.72	7.56	7.56	7.00	0.4	27.03	6.57	14.43	78.57	-0.87	66.94
4	2.0	25	1.000	1.000	7.28	8.17	8.28	8.00	7.28	1.7	28.21	6.54	15.32	78.93	-0.88	65.27
5	0.18934	20	-1.414	0.000	6.89	7.22	7.22	7.22	7.00	0.1	23.79	6.57	12.03	78.35	-0.95	63.70
6	2.31066	20	1.414	0.000	7.44	8.06	8.06	7.78	7.50	2.1	25.52	6.60	13.35	78.93	-1.07	64.13
7	1.25	12.9289	0.000	-1.414	6.17	6.17	7.22	6.22	6.00	1.2	20.03	6.59	11.53	81.06	-1.23	60.18
8	1.25	27.0711	0.000	1.414	6.33	8.06	8.06	8.00	6.28	1.0	28.78	6.59	15.39	77.36	-0.79	67.23
9	1.25	20	0.000	0.000	8.22	8.17	8.17	7.44	8.22	1.1	24.67	6.58	12.16	80.25	-0.98	63.43
10	1.25	20	0.000	0.000	8.00	8.22	8.39	7.50	8.44	1.2	24.54	6.58	12.38	79.86	-0.96	62.94
11	1.25	20	0.000	0.000	8.06	8.06	8.44	7.56	8.33	1.1	24.66	6.58	12.34	80.02	-1.05	63.54
12	1.25	20	0.000	0.000	8.33	8.33	8.39	7.72	8.22	1.1	24.56	6.6	12.61	79.38	-1.04	63.11
13	1.25	20	0.000	0.000	8.17	8.00	8.22	7.61	8.22	1.1	24.58	6.59	12.86	80.17	-1.01	64.08

Table 2 Analysis of variance (ANOVA) for sensory parameters and physico-chemical quality, colour values and viscosity of goat milk lollies

Source of Variation	df	Sum of Squares											
		Flavour	Body and Texture	Colour and Appearance	Melting Quality	Overall Acceptability	Fat (%)	Total solids (%)	pH	Viscosity (c P	L*	a*	b*
Model	5	7.88**	6.64**	3.76**	3.51**	7.25**	3.84**	79.56**	0.0021^{NS}	19.79^{**}	10.37*	0.1315*	42.59**
A	1	0.1764*	1.18**	0.6987**	0.4763**	0.2168*	3.82**	3.01**	0.0003	1.10**	0.0220^{NS}	0.0000^{NS}	0.8333^{NS}
B	1	0.1191*	2.51**	0.9105**	2.62**	0.5030**	0.0183*	76.47**	0.0003^{NS}	16.18**	7.020**	0.1231**	40.860**
AB	1	0.0702^{NS}	0.0196^{NS}	0.0600^{NS}	0.0196^{NS}	0.0006^{NS}	0.0025^{NS}	0.0025^{NS}	0.0012^{NS}	0.1156^{NS}	0.9604^{NS}	0.0072^{NS}	0.0056^{NS}
A^2	1	1.80**	0.2082*	0.8571**	0.0129^{NS}	0.9959**	0.0018^{NS}	0.0049^{NS}	0.0002^{NS}	0.2511^{NS}	2.110*	0.0006^{NS}	0.6875^{NS}
B^2	1	6.48**	2.88**	1.49**	0.3940**	6.06**	0.0018^{NS}	0.0675**	0.0001^{NS}	2.30**	0.4904^{NS}	0.0006^{NS}	0.3050^{NS}
Residual	7	0.1243	0.1432	0.1376	0.0922	0.2661	0.0155	0.0141	0.0016	0.5977	2.410	0.0302	3.160
Lack of Fit	3	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Pure Error	4	0.0681	0.0681	0.0567	0.0459	0.0771	0.0080	0.0141	0.0003	0.2928	0.4753	0.0059	0.7766
R^2		0.9845	0.9789	0.9647	0.9744	0.9646	0.9960	0.9998	0.5764	0.9707	0.9707	0.8131	0.9310
R^2_{adj}		0.9734	0.9638	0.9395	0.9561	0.9393	0.9931	0.9997	0.2739	0.9498	0.9498	0.6796	0.8817
APV$^{\Phi}$		23.23	23.41	14.74	22.45	16.77	61.16	286.52	4.7374	20.2660	20.2660	7.8588	14.0143

**significant at p<0.01; *significant at p<0.05; NS: non-significant; A: Fat; B: Sweetener; $^{\Phi}$ adequate precision value

Table 3 Constraints used for the optimization of goat milk lollies

Particular	Goat Milk Lollies Goal	Importance
Variables		
Fat Level (%)	range (0.5 to 2.0)	3
Sweetener Level (%)	range (15 to 25)	3
Responses		
Flavour	maximize	3
Body and Texture	maximize	3
Colour & Appearance	maximize	3
Melting Quality	maximize	3
Overall Acceptability	maximize	3

Note: goal for all other responses were none

Table 4 RSM Solution for preparation of goat milk lollies

	Goat Milk
Fat (%)	1.50
Sweetener (%)	21.27
Desirability	0.938

Table 5 Predicted vs. Experimental value of the responses for optimized milk lollies prepared from goat milk

Particular	Goat Milk		
	Predicted Value	Actual Value	$t_{0.05}$
Flavour	8.13	8.11±0.07	0.261^{NS}
Body and Texture	8.36	8.28±0.07	1.224^{NS}
Colour and Appearance	8.49	8.41±0.08	1.029^{NS}
Melting Quality	7.77	7.70±0.08	0.864^{NS}
Overall Acceptability	8.04	7.96±0.05	1.457^{NS}
Fat (%)	1.37	1.33±0.02	2.200^{NS}
Total Solids (%)	25.59	25.49±0.06	1.625^{NS}
pH	6.58	6.57±0.01	1.000^{NS}
L*	79.64	79.59±0.03	1.987^{NS}
a*	-0.98	-0.96±0.01	1.941^{NS}
b*	63.94	63.78±0.04	2.203^{NS}
Viscosity of Mix (c P)	13.03	12.94±0.04	2.235^{NS}
Desirability	0.938		

Predicted values from RSM; Actual values are Mean ± SE. $t_{0.05}$ = calculated t-value (α=0.05); NS = non-significant (p>0.05)

Table 6 Sensory, compositional, physico-chemical, functional, colour & microbial characteristics of optimized goat milk lollies

Parameter	Goat milk lollies
Sensory attributes (9-point hedonic scale)	
Flavour	8.11 ± 0.03
Body and texture	8.28 ± 0.03
Colour and appearance	8.41 ± 0.02
Melting quality	7.70 ± 0.07
Overall acceptability	7.96 ± 0.04
Compositional attributes (%)	
Fat	1.33 ± 0.02
Total solids	25.49 ± 0.06
Protein	3.64 ± 0.01
Total carbohydrate	19.91 ± 0.06
Ash	0.599 ± 0.001
Physico-chemical properties	
Acidity (% lactic acid)	0.162 ± 0.003
pH	6.58 ± 0.01
Melting rate (mL/h)	98.92 ± 0.44
Viscosity of mix (c P)	12.94 ± 0.04
Functional property	
DPPH radical scavenging activity (%)	13.99 ± 0.50
Colour values	
L* (lightness)	79.59 ± 0.03
a* (redness/greenness)	−0.96 ± 0.01
b* (yellowness/blueness)	63.78 ± 0.03
Microbial count	
Aerobic plate count (log_{10} CFU/mL)	4.37 ± 0.04
Coliform count (log_{10} CFU/mL)	ND
Yeast and mold count (log_{10} CFU/mL)	ND

Values are Mean ± SE. ND=Not Detected

Figure 1a

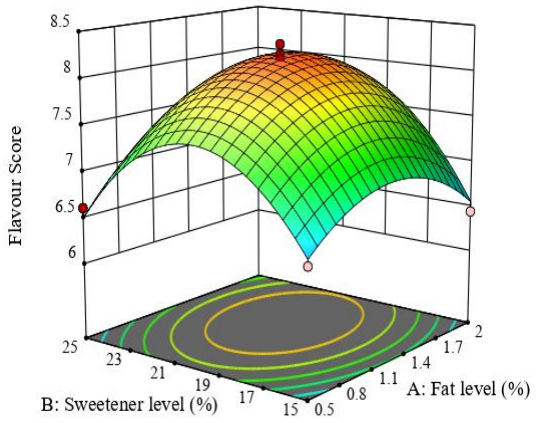


Figure 1b

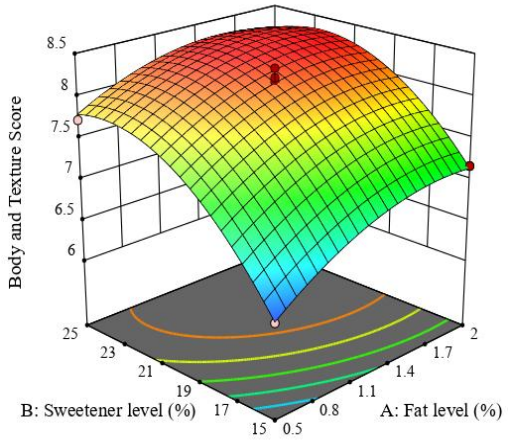


Figure 1c

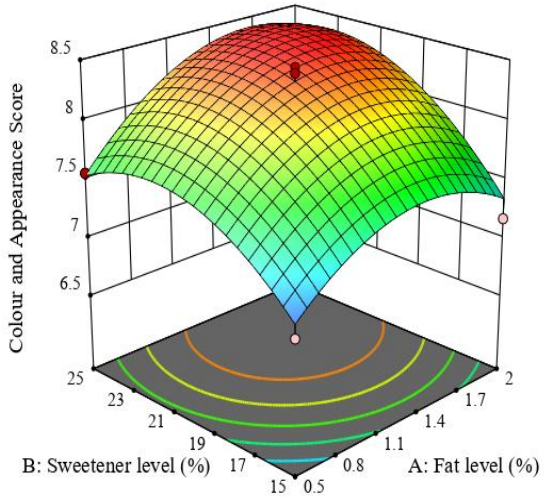
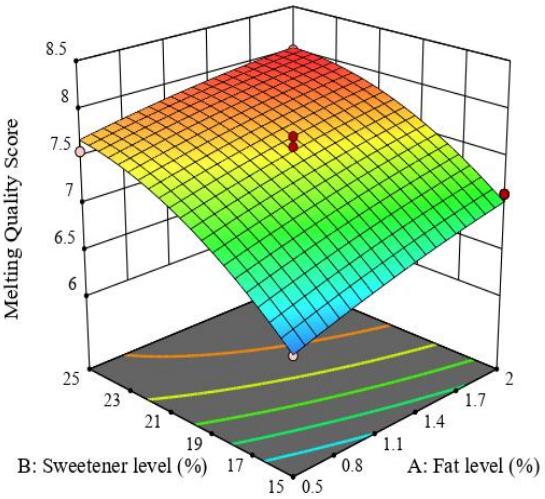


Figure 1d



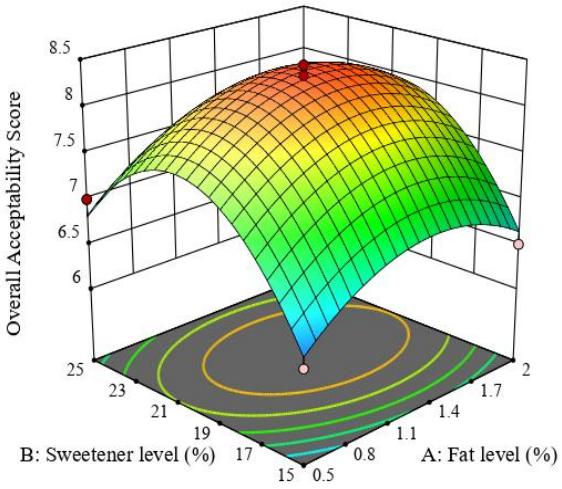


Figure 1e

Figure 1a-e Response surface plot of sensory attributes for goat milk lollies

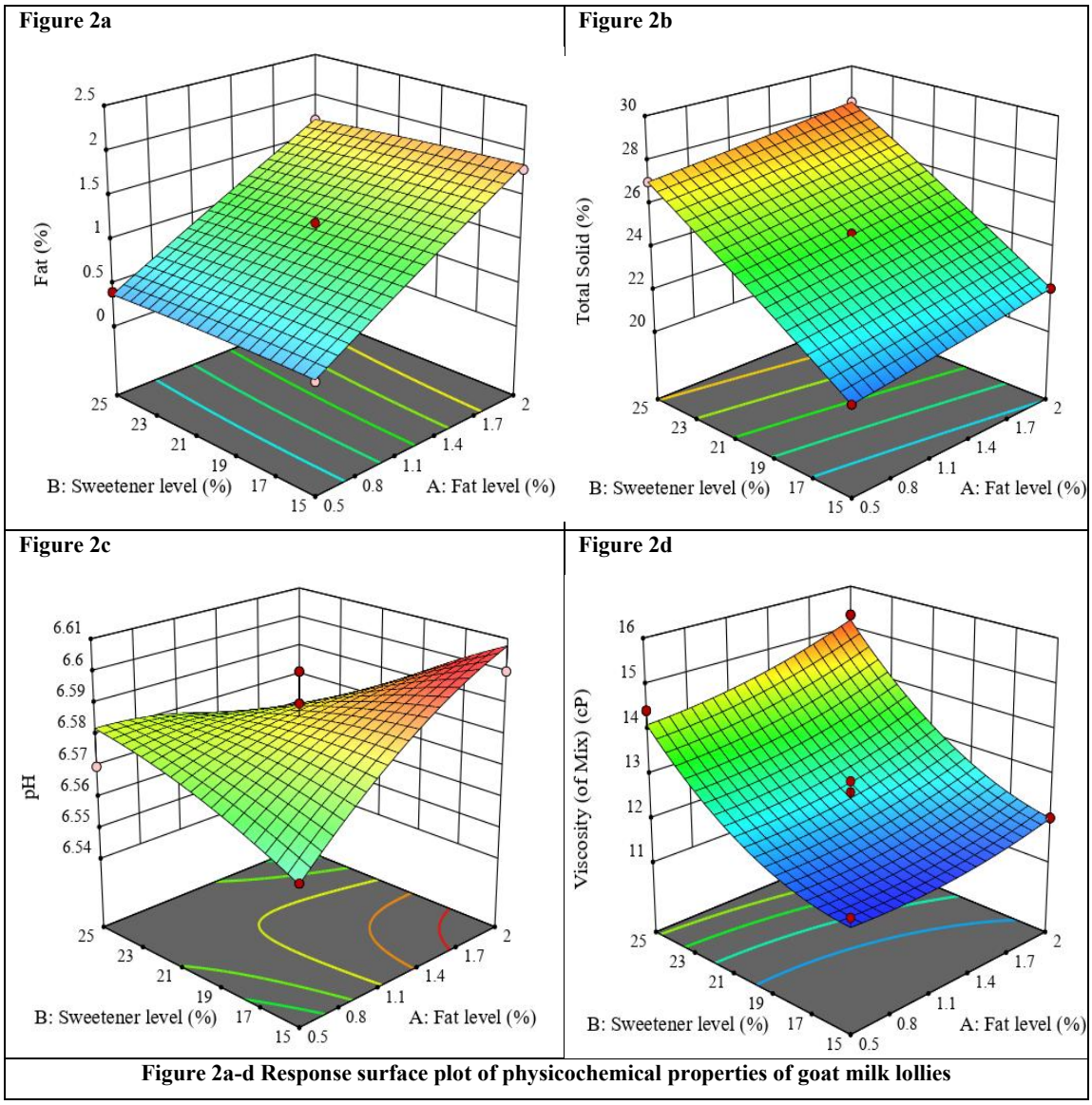


Figure 2a-d Response surface plot of physicochemical properties of goat milk lollies

leading to inferior structural properties and reduced textural acceptability. The balance between frozen ice crystals and the unfrozen matrix is a key determinant of texture, as excessive solids or fat can disrupt structural stability and alter ice crystal growth behaviour (Walstra et al., 2005; Wu et al., 2025). Therefore, the regression model clearly demonstrates that moderate levels of fat and sweetener are essential for achieving optimal body and texture characteristics in goat milk lollies, whereas excessive concentrations of either component negatively affect the structural stability and mouthfeel of the frozen product.

Effect of Fat and Sweetener Levels on Colour and Appearance of Goat Milk Lollies

The colour and appearance scores of goat milk lollies were significantly influenced ($p < 0.05$) by variations in fat and sweetener levels, as presented in Table 1 and illustrated by the response surface plots (Figure 1c). The observed scores ranged from 6.94 to 8.44, indicating that formulation variables had a substantial effect on the visual quality of the product. The highest colour and appearance scores were obtained near the central region of the experimental design, suggesting that moderate levels of fat and sweetener contribute to improved visual attributes of goat milk lollies. The relationship between formulation variables and colour and appearance score was described by the following second-order polynomial regression model:

Figure 3a

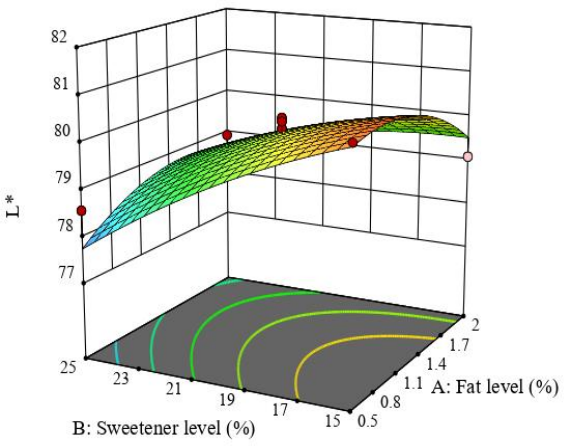


Figure 3b

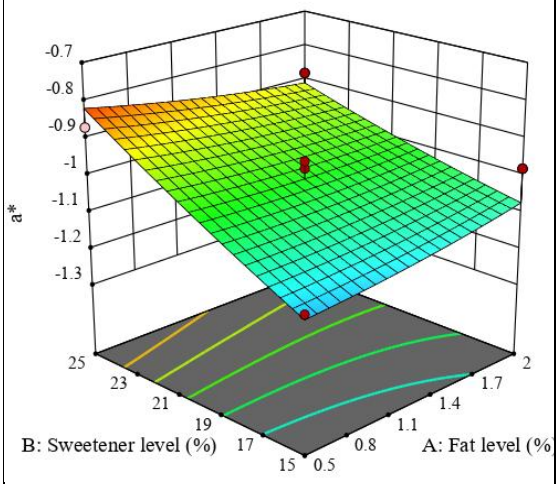


Figure 3c

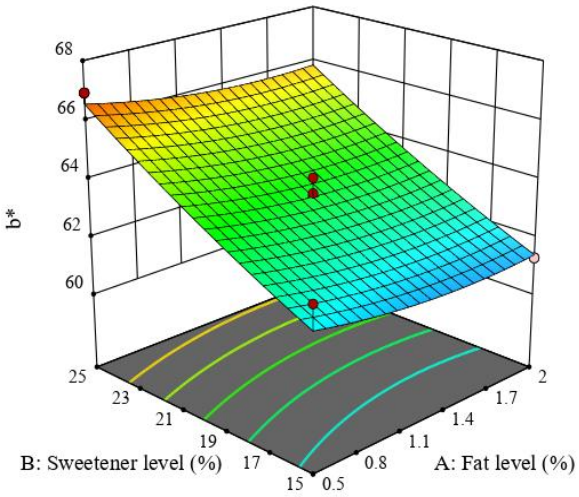


Figure 3a-c Response surface plot of colour values of goat milk lollies

Effect of Fat and Sweetener Levels on Colour and Appearance of Goat Milk Lollies

The colour and appearance scores of goat milk lollies were significantly influenced ($p < 0.05$) by variations in fat and sweetener levels, as presented in Table 1 and illustrated by the response surface plots (Figure 1c). The observed scores ranged from 6.94 to 8.44, indicating that formulation variables had a substantial effect on the visual quality of the product. The highest colour and appearance scores were obtained near the central region of the experimental design, suggesting that moderate levels of fat and sweetener contribute to improved visual attributes of goat milk lollies. The relationship between formulation variables and colour and appearance score was described by the following second-order polynomial regression model:

Colour and Appearance = $8.32 + 0.2955A + 0.3374B + 0.1225AB - 0.3510A^2 - 0.4635B^2$

where A represents fat content (%) and B represents sweetener level (%).

The regression model was highly significant ($p < 0.01$), confirming that both fat and sweetener levels played a crucial role in determining the visual characteristics of goat milk lollies. The positive coefficients of the linear terms (A and B) indicate that increasing fat and sweetener concentrations within the experimental range improved the colour and appearance scores. The positive linear effect of fat ($p < 0.01$) suggests that increasing fat levels enhanced the surface gloss and uniformity of the product (Table 2). Similarly, sweetener exhibited a positive and highly significant linear effect ($p < 0.01$) on colour and appearance scores. Increasing sweetener levels increased the total solids content of the mix, which reduced the formation of ice crystals and produced a smoother and brighter surface.

The quadratic coefficients of fat (A^2) and sweetener (B^2) were negative and highly significant ($p < 0.01$), indicating that excessive levels of these components adversely affected the visual quality of the product. As illustrated by the response surface plots, colour and appearance scores declined when fat and sweetener concentrations exceeded the optimum range. Excessive fat content may increase surface opacity and dullness, thereby reducing visual brightness. Milk fat globules scatter light within the frozen matrix, and higher fat concentrations may enhance light scattering, which can reduce visual brightness and impart a more opaque appearance to dairy products (Walstra et al., 2005; Milovanovic et al., 2020). Similarly, high sweetener levels may increase the proportion of unfrozen water in the system by lowering the freezing point of the mix, resulting in a soft structure that may reduce firmness and negatively influence the visual stability of the frozen matrix (Goff & Hartel, 2013; Wu et al., 2025).

Effect of Fat and Sweetener Levels on Melting Quality of Goat Milk Lollies

The melting quality scores of goat milk lollies were significantly influenced ($p < 0.01$) by variations in fat and sweetener levels, as presented in Table 1 and illustrated by the response surface plots (Figure 1d). The melting quality scores ranged from 6.22 to 8.00, indicating that formulation variables had a pronounced effect on the melting behaviour and structural stability of the product during meltdown.

The relationship between formulation variables and melting quality score was described by the following second-order polynomial regression model:

$$\textbf{Melting Quality} = 7.57 + 0.2440A + 0.5722B - 0.0700AB - 0.0430A^2 - 0.2380B^2$$

where A represents fat content (%) and B represents sweetener level (%).

The regression coefficients indicate that both fat and sweetener had positive linear effects on melting quality scores. Among the two variables, sweetener exerted a highly significant linear effect ($p < 0.01$) on melting quality. The lowest melting quality scores were observed at the lowest sweetener level (12.93%), whereas higher scores were obtained at increased sweetener concentrations (approximately 25–27%).

Moderate increases in sweetener concentration improved melting quality primarily due to its influence on the freezing characteristics of the mix. Sugars depress the freezing point of the system and increase the proportion of the unfrozen serum phase, which helps in controlling ice crystal growth and improving the smoothness. A balanced unfrozen phase contributes to a more uniform and controlled meltdown, thereby enhancing the melting quality of frozen dairy products. However, the quadratic coefficient of sweetener (B^2) was negative and highly significant ($p < 0.01$) (Table 2), indicating that excessive sweetener levels adversely affected melting behaviour. High sugar concentrations increase the amount of unfrozen water in the system, which weakens the frozen matrix and results in rapid structural collapse, loss of shape and reduced resistance to meltdown.

Fat content also showed a positive and significant linear effect ($p < 0.01$) on melting quality scores. Increasing fat levels improved melting quality, as reflected by the upward trend along the fat axis in the response surface plots. This improvement can be attributed to the role of milk fat during freezing, where partial coalescence of fat globules forms a weak but stable fat network surrounding air cells and ice crystals. This network strengthens the structural framework of the frozen product and delays collapse during melting, thereby improving resistance to meltdown and enhancing shape retention (Muse & Hartel, 2004; Goff & Hartel, 2013). The stabilization of air cells and interaction between fat globules, ice crystals and the serum phase contribute to a more cohesive frozen matrix, which slows the rate of structural breakdown during melting (Walstra et al., 2005; Wu et al., 2025).

Effect of Fat and Sweetener Levels on Overall Acceptability of Goat Milk Lollies

The combined influence of formulation variables, namely fat and sweetener levels, on the overall acceptability of goat milk lollies is illustrated by the three-dimensional response surface plots shown in Figure 1e, while the corresponding experimental data are presented in Table 1. The overall acceptability scores varied significantly ($p < 0.01$) with changes in fat and sweetener levels. The observed scores ranged from 6.00 to 8.44, indicating that formulation variables had a pronounced effect on overall acceptability of the product.

The relationship between formulation variables and overall acceptability score was described by the following second-order polynomial regression equation:

$$\textbf{Overall Acceptability} = 8.03 + 0.1646A + 0.2507B - 0.0125AB - 0.3784A^2 - 0.9334B^2$$

where A represents fat content (%) and B represents sweetener level (%).

The quadratic regression model for overall acceptability was highly significant ($p < 0.01$), indicating that the response did not increase in a linear manner. The positive coefficients of the linear terms (A and B) suggest that increasing fat and sweetener levels initially improved the overall acceptability of goat milk lollies (Table 2). This improvement can be attributed to the enhancement of key sensory attributes such as flavour, body and texture, colour and appearance, and melting quality, which collectively determine the overall acceptability of the product.

Among the two variables, sweetener showed a relatively stronger linear influence compared to fat, indicating that sweetness level plays an important role in determining overall consumer acceptance of goat milk lollies.

At the quadratic level, both fat (A^2) and sweetener (B^2) exhibited negative and significant effects ($p < 0.05$) on overall acceptability scores. This indicates that excessive levels of either fat or sweetener adversely affected the sensory acceptance of the product.

The interaction effect between fat and sweetener (AB) was negative but statistically non-significant ($p > 0.05$), suggesting that both variables influenced overall acceptability largely independently rather than synergistically. Nevertheless, the response surface plots indicated that the highest overall acceptability was obtained when both fat and sweetener were maintained within an intermediate formulation range.

Effect of Fat and Sweetener Levels on Composition and Physicochemical Properties of Goat Milk Lollies

The fat content of goat milk lollies increased with an increase in the formulated fat level (Table 1). The response of fat content to formulation variables is further illustrated by the three-dimensional response surface plots shown in Figure 2a. The fat content of goat milk lollies varied from 0.10 to 2.10 % across the experimental treatments. The lowest fat content was recorded in the treatment where goat milk lollies were prepared with the lowest formulated fat level (approximately 0.19 %), whereas the highest fat content was observed at the maximum fat level (approximately 2.31 %).

The relationship between formulation variables and fat content was described by the following second-order polynomial regression model:

$$\textbf{Fat (\%)} = 1.12 + 0.6911A - 0.0479B - 0.0250AB - 0.0162A^2 - 0.0162B^2$$

where A represents fat content (%) and B represents sweetener level (%).

Analysis of variance indicated that the regression model for fat content was highly significant ($p < 0.01$). At the linear level, fat (A) showed a positive and highly significant effect ($p < 0.01$) on the measured fat content of goat milk lollies (Table 2). This behaviour is clearly reflected by the uniform gradient observed along the fat axis in the response surface plots (Figure 2a), indicating that increasing fat levels in the formulation resulted in a corresponding increase in fat concentration in the finished product.

Effect of Fat and Sweetener Levels on Total Solids Content of Goat Milk Lollies

The total solids content of goat milk lollies varied significantly ($p < 0.01$) with changes in fat and sweetener levels, as presented in Table 1, and the combined influence of these formulation variables is illustrated through the response surface plots in Figure 2b. The total solids content ranged from 20.03 to 28.78 %, indicating that formulation composition had a pronounced effect on the overall dry matter content of the product (Table 2).

The relationship between formulation variables and total solids content was described by the following second-order polynomial regression model:

$$\textbf{Total Solids (\%)} = 24.60 + 0.6133A + 3.0900B - 0.0250AB + 0.0265A^2 - 0.0985B^2$$

where A represents fat content (%) and B represents sweetener level (%).

The regression model for total solids content was highly significant ($p < 0.01$), confirming that both fat and sweetener contributed to variations in the total solids of goat milk lollies. The positive linear coefficients of fat (A) and sweetener (B) indicate that increasing the levels of these components resulted in a corresponding increase in the total solids content of the product. Among the two variables, the effect of sweetener was more pronounced, as indicated by the larger regression coefficient for sweetener compared to fat.

Fat content exhibited a positive and significant linear effect ($p < 0.01$) on the total solids content of goat milk lollies. Although the magnitude of this effect was smaller compared to that of sweetener, the observed variation in total solids even at constant sweetener levels indicates that changes in fat concentration contributed measurably to the overall solids content.

The interaction effect between fat and sweetener (AB) was relatively small, indicating minimal combined influence of these variables on total solids content. The quadratic coefficient of fat (A^2) was positive but small, suggesting a slight increase in total solids at higher fat levels. In contrast, the quadratic coefficient of sweetener (B^2) was negative, indicating that the increase in total solids gradually stabilized at higher sweetener concentrations.

Effect of Fat and Sweetener Levels on pH of Goat Milk Lollies

The pH of goat milk lollies varied narrowly from 6.54 to 6.60 across different fat and sweetener levels (Table 1; Figure 2c). The relationship was expressed by the quadratic regression equation:

$$\textbf{pH} = 6.59 + 0.0066A - 0.0063B - 0.0175AB - 0.0055A^2 - 0.0030B^2$$

where A represents fat content (%) and B represents sweetener level (%).

The model was statistically non-significant ($p > 0.05$), indicating negligible effects of formulation variables on pH. This may be attributed to the neutral nature of sucrose and milk fat and the buffering capacity of milk proteins and mineral salts. Similarly, Low et al. (2015) reported unchanged pH (6.60) at 15–21% sucrose, while Budus et al. (2024) observed minimal pH variation (approximately 6.4) when sugar content was reduced from 18% to 12% in ice cream.

Effect of Fat and Sweetener Levels on Viscosity of Goat Milk Lollies Mix

The viscosity of goat milk lollies mix increased with variations in fat and sweetener levels, as presented in Table 1, and the response behaviour of mix viscosity across the experimental formulation range is illustrated in Figure 2d. The viscosity values ranged from 11.53 to 15.39 cP, indicating a clear influence of formulation variables on the viscosity of the mix.

The relationship between formulation variables and viscosity was described by the following second-order polynomial regression equation:

$$\textbf{Viscosity (cP)} = 12.47 + 0.3708A + 1.4200B + 0.1700AB + 0.1900A^2 + 0.5750B^2$$

where A represents fat content (%) and B represents sweetener level (%).

Regression analysis indicated that the viscosity model was highly significant ($p < 0.01$), confirming that both fat and sweetener levels significantly influenced the viscosity of goat milk lollies mix (Table 2). The positive coefficients of the linear terms (A and B) indicate that increasing the concentration of fat and sweetener resulted in a corresponding increase in mix viscosity. Among the two variables, sweetener exerted the strongest influence, as indicated by its relatively higher regression coefficient.

At the linear level, sweetener showed a positive and highly significant effect ($p < 0.01$) on viscosity. This increase can be attributed to the rise in total soluble solids, which enhances water binding in the serum phase and increases the viscosity of the continuous phase. Higher sugar concentrations reduce the amount of free water available in the system and increase the density and resistance to flow of the mix (Goff and Hartel, 2013; Marshall et al., 2003).

Fat content also exhibited a positive and significant linear effect ($p < 0.05$) on the viscosity of goat milk lollies mix. Increasing fat levels increase the volume fraction of the dispersed phase, which contributes to higher resistance to flow. In addition, interactions between fat globules and milk proteins can promote the formation of a weak structural network in the mix, thereby increasing viscosity. However, the magnitude of the fat effect was lower than that of sweetener, indicating that sweetener played a dominant role in viscosity development within the studied formulation range.

The interaction term (AB) was positive but relatively small, suggesting that simultaneous increases in fat and sweetener produced only a moderate combined effect on viscosity. The positive quadratic coefficients (A^2 and B^2) indicate that viscosity increased progressively at higher levels of fat and sweetener, reflecting the cumulative effects of increased dispersed phase volume and higher serum phase solids.

Effect of Fat and Sweetener Levels on Colour Parameters of Goat Milk Lollies

Effect on L* Value

The L* value (0–100), which represents the lightness of the product, varied from 77.36 to 81.06 in goat milk lollies, as presented in Table 1, and the response behaviour of lightness across different combinations of fat and sweetener levels is illustrated in Figure 3a. Higher L* values indicate a lighter and brighter appearance of the product. Goat milk lollies exhibited relatively high L* values, reflecting a lighter and whiter appearance.

The relationship between formulation variables and L* value was described by the following second-order polynomial regression equation:

$$\textbf{L*} = 79.94 - 0.0525A - 0.9366B + 0.4900AB - 0.5505A^2 - 0.2655B^2$$

where A represents fat content (%) and B represents sweetener level (%)

Goat milk typically contains lower levels of β-carotene compared with cow milk and possesses distinct casein micelle and fat globule characteristics, which enhance light scattering and contribute to higher perceived lightness in dairy products (Milovanovic et al., 2020; Garzón et al., 2024). Regression analysis indicated that sweetener level exerted a significant linear effect ($p < 0.01$) on L* values. The negative coefficient of sweetener suggests that increasing sweetener levels slightly reduced the lightness of goat milk lollies. This trend is evident in the response surface plots where higher sweetener concentrations correspond to a gradual decline in L* values.

The decrease in lightness at higher sweetener concentrations can be explained by the increase in dissolved solids within the serum phase, which alters the refractive index and light transmission properties of the matrix. Higher concentrations of soluble solids modify the optical properties of the serum phase and influence light scattering behaviour within the frozen matrix (Walstra et al., 2005; Milovanovic et al., 2020). As the concentration of soluble solids increases, the refractive index difference between dispersed phases and the continuous serum phase changes, which can reduce light reflectance and slightly decrease the perceived brightness of the product. Consequently, increased soluble solids may lead to a marginal reduction in surface brightness, resulting in a slightly duller appearance of the frozen product (Goff & Hartel, 2013).

Effect on a* Value

The a* value represents the red–green colour axis, where positive values indicate redness and negative values indicate greenness. The a* values of goat milk lollies remained negative across all treatments and ranged from –1.23

to –0.79. The response behaviour of a* values across different combinations of fat and sweetener levels is illustrated in Figure 3b.

The regression relationship between formulation variables and a* value was expressed as:

$$a^* = -1.01 - 0.0025A + 0.1240B - 0.0425AB + 0.0096A^2 + 0.0096B^2$$

where A represents fat content (%) and B represents sweetener level (%)

Regression analysis showed that sweetener level had a highly significant linear effect ($p < 0.01$) on the a* value of goat milk lollies. The positive regression coefficient indicates that increasing sweetener levels shifted the a* values towards zero, thereby reducing the degree of greenness. This behaviour is also evident from the response surface plots where higher sweetener concentrations correspond to less negative a* values.

The slight increase in a* values with increasing sweetener concentration may be attributed to changes in surface structure and optical scattering behaviour. Higher sweetener levels increase total solids and reduce visible ice-phase defects, producing a smoother and more uniform surface. Such structural modifications influence light reflection and visual perception, leading to subtle shifts in colour coordinates even in the absence of additional pigments (Walstra et al., 2005; Milovanovic et al., 2020). In frozen dairy systems, variations in total solids and microstructure can modify light scattering and surface reflectance properties, thereby affecting instrumental colour parameters such as a* and b* values (Goff & Hartel, 2013). Comparable formulation-driven changes in visual characteristics have been reported by Hashim and Shamsi (2016), who observed modifications in surface appearance and firmness of ice cream when sucrose was progressively replaced with date syrup.

Effect on b* Value

The b* value represents the yellow–blue colour axis, where positive values indicate increased yellowness and negative values indicate blueness. The b* values of goat milk lollies ranged from 60.18 to 67.23, indicating moderate to high yellowness of the product. The regression model describing the relationship between formulation variables and b* value was expressed as:

$$b^* = 63.42 - 0.3227A + 2.2600B - 0.0375AB + 0.3144A^2 + 0.2094B^2$$

where A represents fat content (%) and B represents sweetener level (%)

The regression model for b* values was highly significant ($p < 0.01$), indicating that formulation variables produced measurable changes in yellowness. A yellow colour was incorporated in the formulation to enhance the visual appeal of the milk lollies; therefore, the observed b* values represent the combined influence of added colour, formulation composition, and optical characteristics of the frozen matrix.

Regression analysis revealed that sweetener exhibited a positive linear effect on b* values, indicating that increasing sweetener concentration enhanced yellowness of the product. In contrast, the linear and quadratic effects of fat, the quadratic effect of sweetener, and the interaction between fat and sweetener were non-significant ($p > 0.05$).

The increase in b* values with higher sweetener levels can be explained by modifications in the serum phase composition and optical properties of the product. Higher sweetener concentrations increase total soluble solids and raise the refractive index of the unfrozen phase, making the product appear less translucent and allowing the yellow colour, originating from added colour and minor milk pigments, to become more visually prominent. Similar relationships between solids concentration, refractive index and colour perception in dairy systems have been reported by Walstra et al. (2005) and Goff & Hartel (2013).

Optimization of Fat and Sweetener Levels for Goat Milk Lollies

Optimization of goat milk lolly formulation was performed using the numerical optimization function of RSM, with the objective of maximizing the overall acceptability score. The optimization constraints applied to the independent variables and response parameters are presented in Table 3.

For goat milk lollies, fat level (%) was constrained within the range of 0.5–2.0 %, while sweetener level (%) was constrained between 15–25 %, based on preliminary trials, sensory requirements, and product formulation considerations. Among the response variables, flavour, body and texture, colour and appearance, melting quality, and overall acceptability were set with the goal of maximization, and each response was assigned equal importance. All other responses were set to "none", ensuring that the optimization process was primarily driven by sensory attributes.

The numerical optimization predicted an optimal formulation consisting of 1.50 % fat and approximately 21.27 % sweetener, with a high overall desirability value, indicating strong agreement among the predicted responses. The optimized solution demonstrates that moderate levels of both fat and sweetener are required to achieve maximum sensory acceptability in goat milk lollies.

The predicted optimum levels are consistent with the trends observed for individual sensory attributes, where excessive levels of fat or sweetener resulted in reduced sensory scores, whereas intermediate levels produced balanced flavour, improved body and texture, desirable melting characteristics, and enhanced overall acceptability.

The optimized fat level of 1.50 % represents the minimum fat requirement for achieving acceptable sensory quality among the studied formulations. Similarly, the optimized sweetener level of approximately 21.27 % falls

within a narrow optimum range identified during formulation trials. At this concentration, sweetener provides adequate sweetness, contributes to total solids, thereby improving body and texture, structural stability, and melting resistance of the frozen product (Muse & Hartel, 2004; Goff & Hartel, 2013).

At lower fat and sweetener levels, goat milk lollies exhibited weaker flavour intensity and inferior textural characteristics, whereas higher sweetener levels produced excessive sweetness and reduced flavour balance, leading to lower sensory acceptance. Therefore, the optimized formulation of 1.50 % fat and 21.27 % sweetener represents a balanced composition that maximizes sensory quality while preserving the low-fat profile of goat milk lollies.

Comparison of Predicted and Experimental Values of Optimized Goat Milk Lollies

The predicted and experimental values obtained for the optimized formulation of goat milk lollies are presented in Table 5, demonstrating successful validation of the optimized model developed using RSM. For all evaluated parameters, including sensory attributes, physico-chemical characteristics, colour parameters, pH, and mix viscosity, the differences between predicted and experimental values were statistically non-significant ($p > 0.05$). This close agreement confirms that the developed regression models were adequate, reliable, and capable of accurately predicting product responses within the selected optimization range.

Under optimized conditions, goat milk lollies exhibited high overall acceptability scores (~8.0), indicating good sensory acceptance of the product. The obtained acceptability suggests that the optimization process effectively balanced fat and sweetener levels to improve overall sensory quality. This optimization is particularly important for goat milk products because goat milk contains relatively higher proportions of short- and medium-chain fatty acids such as caproic (C6:0), caprylic (C8:0), and capric (C10:0), which are associated with the characteristic "goaty" flavour (Raynal-Ljutovac et al., 2008; Clark & Mora García, 2017; Nayik et al., 2021). If not properly balanced, these compounds may negatively influence sensory perception. The optimized formulation successfully moderated the perception of this characteristic flavour through an appropriate combination of sweetness and fat level, thereby improving flavour acceptability.

The body and texture scores of goat milk lollies showed non-significant differences ($p > 0.05$) between predicted and experimental values, confirming the reliability of the RSM model. The slightly lower mix viscosity of goat milk, due to its comparatively lower total solids, resulted in marginally lower body and texture scores; however, the values remained within the acceptable sensory range (Clark & Mora García, 2017; Carvalho et al., 2022).

Similarly, melting quality scores closely matched the predicted values and did not differ significantly ($p > 0.05$), indicating that the optimized formulation provided desirable melting behaviour. The fat content, total solids, pH, and instrumental colour values also showed non-significant differences ($p > 0.05$) between predicted and experimental results, confirming the accuracy and adequacy of the developed RSM model and indicating that the optimized formulation maintained consistent physicochemical and visual quality.

Compositional, Physico-Chemical, Sensory and Microbiological Analysis of Optimized Goat Milk Lollies

Sensory Attributes of Optimized Goat Milk Lollies

The optimized goat milk lollies obtained high sensory scores, indicating good overall acceptability despite the inherent flavour characteristics of goat milk (Table 6). The flavour score (8.11) indicated excellent flavour perception and optimization of fat and sweetener levels effectively balanced sweetness and flavour intensity, thereby minimizing undesirable flavour notes. The body and texture score (8.28) reflected a smooth and acceptable structure; despite relatively lower mix viscosity due to the naturally lower total solids content of goat milk, the optimized formulation maintained satisfactory textural characteristics. The colour and appearance score (8.41) indicated a visually appealing product with uniform colour and surface characteristics. The melting quality score (7.70) suggested acceptable resistance to melting and adequate shape retention, which can be attributed to the combined effect of optimized sweetener level controlling freezing point depression and moderate fat content contributing to structural stability of the frozen matrix. Consequently, the overall acceptability score (7.96) confirmed good consumer acceptance of the optimized goat milk lollies.

Compositional Characteristics of Optimized Goat Milk Lollies

The compositional characteristics of the optimized goat milk lollies are presented in Table 6. The product contained 1.33 % fat, confirming the successful development of a low-fat frozen dairy product without compromising sensory quality, as moderate fat reduction in goat milk frozen desserts has been reported to maintain acceptable sensory attributes when supported by appropriate formulation design (Carvalho et al., 2022). The total solids content was 25.49 %, which was sufficient to provide structural stability and acceptable texture, although goat milk inherently contains lower total solids than buffalo or sheep milk, thereby influencing the rheological behaviour of frozen dairy systems (Al-Fayad, 2022; Pires et al., 2022). The protein content (3.64 %) corresponded well with the natural protein composition of goat milk and contributed to water binding, viscosity development and structural stability of the frozen matrix. The carbohydrate content (19.91 %), primarily derived from added sweetener and lactose, played an important role in freezing point depression, sweetness perception and overall product texture. The ash content (0.60 %) reflected

the mineral composition of goat milk and contributed to ionic balance and protein–mineral interactions, which are important for maintaining stability of the frozen dairy product.

Physico-Chemical Characteristics of Optimized Goat Milk Lollies

The physico-chemical characteristics of optimized goat milk lollies are presented in Table 6. The titratable acidity was 0.162 % lactic acid, while the pH was 6.58. Goat milk generally exhibits slightly lower titratable acidity due to its relatively lower mineral buffering capacity and differences in casein micelle structure. The melting rate of optimized goat milk lollies was 98.92 mL/h, indicating comparatively faster melting behaviour, which can be attributed to the lower total solids content and reduced mix viscosity, resulting in decreased structural resistance and faster drainage of the unfrozen serum phase during melting. The mix viscosity was 12.94 cP, reflecting the inherently lower solids content of goat milk; however, the optimized formulation maintained acceptable sensory and structural characteristics.

Antioxidant Activity of Optimized Goat Milk Lollies

The DPPH scavenging activity was 13.99%, indicating moderate antioxidant capacity (Table 6). The antioxidant activity can be attributed to the presence of milk proteins, bioactive peptides and naturally occurring antioxidant components, which remain relatively stable during frozen storage. The comparatively lower antioxidant activity observed in goat milk lollies agrees with earlier reports indicating that goat milk generally exhibits lower DPPH scavenging capacity compared to other dairy species due to reduced levels of fat-soluble antioxidant vitamins and differences in mineral and protein composition (El-Fattah et al., 2020; Stobiecka et al., 2022). Nevertheless, the results confirm that goat milk-based frozen desserts retain measurable antioxidant functionality after formulation optimization.

Viscosity of Optimized Goat Milk Lollies

The viscosity of the optimized goat milk lolly mix was 12.94 cP (Table 6), reflecting the rheological behaviour of a low-fat, moderate-solids frozen dairy formulation. The relatively lower viscosity is mainly attributed to the inherent compositional characteristics of goat milk, including lower total solids, smaller casein micelles and reduced casein–calcium phosphate interactions, which limit extensive protein–protein and protein–water interactions. These structural characteristics result in a less dense serum phase and reduced resistance to flow, leading to lower viscosity compared to higher-solids milk systems (Pires et al., 2022). However, unlike ice cream systems, milk lollies involve minimal shear and no intentional air incorporation, and therefore lower viscosity did not adversely affect product quality. The optimized formulation ensured adequate mix flowability while maintaining acceptable body, texture and melting behaviour.

Colour Characteristics of Optimized Goat Milk Lollies

The colour characteristics of optimized goat milk lollies remained within acceptable limits for milk-based frozen desserts (Table 6). The L* value was 79.59, indicating high lightness and a visually appealing appearance due to uniform light scattering within the frozen matrix. The a* value (–0.96) remained on the negative side of the red–green axis, confirming the absence of undesirable reddish tone. The b* value was 63.78, representing moderate yellowness influenced primarily by the added colour in the formulation. Goat milk naturally contains lower carotenoid levels compared to cow milk; therefore, the yellowness observed in the product was mainly formulation-driven.

Microbiological Quality of Optimized Goat Milk Lollies

The aerobic plate count (APC) was 4.37$\log_{10}$ cfu/mL, which remained within the acceptable limits for frozen dairy products specified under the Food Safety and Standards Regulations (FSSR, 2011). Furthemore, coliforms, yeast and moulds were not detected, indicating effective pasteurization, hygienic processing and proper maintenance of frozen storage conditions. The absence of such microorganisms confirms good manufacturing practices.

Conclusion

The present investigation demonstrated the development and optimization of a low-fat goat milk lolly using RSM. The study confirmed that milk fat and sweetener levels play a decisive role in determining the sensory, physicochemical, and melting characteristics of goat milk–based frozen confections. The optimized formulation containing 1.50 % milk fat and 21.27 % sweetener produced a product with high sensory acceptability, particularly in terms of flavour, body and texture, colour and appearance, and melting quality. The developed formulation provides a scientifically validated approach for the commercial utilization of goat milk in frozen dairy products. The product can serve as a low-fat frozen dairy alternative, offering opportunities for small-scale dairy enterprises, cooperative dairies and commercial ice cream manufacturers to diversify their product portfolio. Further research may focus on incorporating natural flavours, functional ingredients and natural colourants to enhance nutritional and sensory value. Studies on long-term storage stability, microstructural characteristics and consumer preference analysis across different demographic groups would provide deeper insight into product acceptance. In addition, the use of natural sweeteners, fat replacers or bioactive ingredients such as probiotics, plant extracts or dietary fibres may further

improve the functional properties of goat milk lollies. Scaling-up studies and techno-economic evaluation will also be essential to facilitate commercial production and market adoption of goat milk-based frozen dairy confections.

Ethical statement

Sensory evaluation was conducted with 20 trained panelists using goat milk lollies prepared from food-grade ingredients. All participants were informed about the product and evaluation procedure, and written informed consent was obtained. Participation was voluntary, with the freedom to withdraw at any stage. Formal ethical approval was not required, as the evaluation involved routine sensory assessment of a food product without invasive procedures.

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