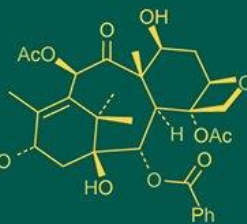
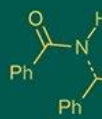


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
 ISSN Online: 2617-4707
 NAAS Rating (2026): 5.29
 IJABR 2026; 10(8): 473-478
www.biochemjournal.com
 Received: 15-06-2026
 Accepted: 18-07-2026

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Optimization of foaming characteristics of bael (*Aegle marmelos*) fruit pulp using Glycerol Mono Stearate (GMS)

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i8f.9623>

Abstract

Bael (*Aegle marmelos*), commonly known as the wood apple or Bengal quince, is a nutritionally and medicinally valuable fruit native to the Indian subcontinent. It is widely cultivated in arid and semi-arid regions due to its resilience to drought and its rich nutrient profile. Bael fruit is a significant source of provitamin A, vitamin C, and B-complex vitamins, along with essential minerals such as calcium, potassium, and iron. Given its dense pulp structure and potential for value-added processing, recent research has focused on optimizing functional and physicochemical properties of Bael-based products. In this context, the present study investigates the effect of glycerol monostearate (GMS) concentration and whipping time (WT) on the foaming properties of Bael pulp, aiming to enhance its application in food and beverage formulations. Bael foams were prepared from pulp by adding different concentrations of GMS (3, 4, 5 and 6%) and whipping at different whipping times (4, 6, 8 and 10 min). Box-Behnken design of experiments was used to optimize the foaming properties. The optimum conditions achieved after the numerical and graphical optimization for maximum foam expansion and stability and minimum foam density were: GMS (6 g/100 g pulp) and WT (10 min). The desirability of 0.998 was achieved at this optimum point. The predicted value of foam density, foam expansion, and foam stability were 0.3800 gcm⁻³, 22.91 % and 0.9861 % at optimum parameters while the experimental value was 0.3795±0.02 gcm⁻³, 22.97±0.02 % and 0.9462±0.02 %, respectively.

Keywords: Bael fruit, glycerol-mono-stearate, foam density, foam expansion, foam stability

1. Introduction

Bael (*Aegle marmelos*), a member of the family Rutaceae, is an indigenous fruit of India and is known by several vernacular and traditional names, including Bengal quince, Bilva, Indian quince, Bel, Belwa, Sriphal, Stone apple, Golden apple, Holy fruit, and Maredu (Sharma *et al.*, 2007) [1]. It is a subtropical, deciduous fruit tree that produces globose fruits characterized by a hard, woody shell, which ranges in color from grey to yellowish. The fruit encloses a soft, yellow to orange-colored, mucilaginous pulp containing numerous seeds. These seeds are densely covered with fine fibrous hairs and are deeply embedded within the thick, sticky, aromatic pulp, which contributes to the distinctive characteristics of the bael fruit (Kaushik *et al.*, 2002) [2].

Virtually every part of the Bael tree possesses considerable utility and has been valued for its nutritional, medicinal, and functional properties. The fruit is particularly rich in sugars, riboflavin, and essential minerals. Traditionally, ripe Bael fruit has been regarded as a tonic and restorative, with laxative properties, and is considered beneficial for maintaining heart and brain health. Mature fruits are especially valued for their digestive properties and have traditionally been used in the management of digestive disorders, including diarrhea and dysentery. Ripe Bael fruits can be processed into a variety of value-added products, such as ready-to-serve nectar, squash, and toffees, whereas unripe fruits are commonly utilized for the preparation of preserves, candies, and dried products in powdered form. The dried and powdered fruit pulp can also serve as a valuable ingredient in various pharmaceutical preparations. Mature bael pulp contains carotenoids and vitamins, while its protein content and secondary metabolites undergo considerable changes during fruit development, particularly from the green stage through maturation up to November (Kaur and Kalia, 2017) [3].

Owing to its high mucilage content and the presence of important secondary metabolites, including coumarin and marmelosin, Bael has been considered beneficial in the management of diabetes (Prajapat *et al.*, 2012) [4]. Furthermore, Bael has been reported to possess potential therapeutic value against several disorders, including cancer, cardiovascular diseases, and ulcers (Maity *et al.*, 2009) [5].



Fig 1: Bael fruit

In foam-mat drying, food liquids and pastes are initially whipped to form a stable foam through the incorporation of suitable foaming agents and are subsequently dried as thin, continuous layers, commonly referred to as mats. The incorporation of air or gas into the material substantially increases its exposed surface area, thereby facilitating rapid moisture removal during drying. The resulting dried product generally possesses a porous structure, which contributes to improved quality, rapid reconstitution, and desirable instant properties (Lewicki, 2006) [6].

Foam-mat drying offers the advantage of being performed at relatively lower temperatures, while the foaming process considerably reduces drying time. In addition, the technique is relatively economical when compared with the drying of non-foamed materials under similar drying conditions. The characteristics of the foam, particularly its expansion and stability, play a critical role in moisture migration during drying and consequently influence the quality of the final product. Foams capable of maintaining their structure without collapse for at least 1 h are generally considered mechanically or thermally stable throughout the drying process (Bates, 1964; Ratti and Kudra, 2006) [7, 8]. Thermally stable foams are able to retain their porous structure during drying, thereby contributing to enhanced reconstitution characteristics of foam-mat-dried products. Foam expansion is commonly evaluated in terms of expansion ratio or foam density, whereas foam stability can be assessed through the measurement of drainage volume.

Several researchers have investigated the application of foam-mat drying using different foaming agents and stabilizers. Falade *et al.* (2003) [9] employed glyceryl monostearate (GMS) and egg albumin for the foam-mat drying of cowpea. Similarly, Muthukumaran *et al.* (2008) [10] investigated the foam-mat drying of egg white using a freeze dryer and evaluated different foam stabilizers, including methylcellulose (MC), propylene glycol alginate, and xanthan gum. Their study reported that the incorporation of 0.125% xanthan gum provided sufficient foam stability, demonstrating its effectiveness as a stabilizing agent during the foam-mat drying process.

Systematic investigations on the drying of Bael (*Aegle marmelos*) fruit pulp remain relatively limited, particularly with respect to foam-mat drying and the optimization of foam formation. Although the foaming characteristics and drying behavior of several tropical fruits, including pineapple, passion fruit, guava, banana, papaya, mango, star fruit, and apple, have been investigated, the available literature does not appear to report systematic studies on the foaming characteristics of Bael fruit pulp.

Therefore, the present investigation was undertaken to systematically evaluate the influence of whipping time and foaming-agent concentration on the foam characteristics of Bael fruit pulp, with particular emphasis on foam density, foam expansion, and foam stability. The foaming conditions were optimized by identifying the combination of whipping time and foaming-agent concentration that resulted in maximum foam expansion (corresponding to minimum foam density) along with maximum foam stability. The optimized foam characteristics were intended to provide a suitable basis for the subsequent foam-mat drying of Bael fruit pulp and the development of a high-quality, porous, and readily reconstitutable dried product.

2. Materials and Methods

According to the method described by Singh and Chaurasiya (2014) [11], the mature bael fruits were thoroughly washed under running tap water to remove any dust, dirt and other unwanted materials. The cleaned fruits were then sliced in half and the pulp was extracted using a bael fruit cutter cum scooper unit. Then, it was mixed with water in a 1:1 (w/v ratio) (Panda *et al.*, 2014) [12]. Then the mixture was weighted by weighing balance. The foaming agent glycerol-mono-stearate at four different concentrations was added in weighted samples and whipped at four different whipping time.

2.1 Foaming Trials

To determine the effect of foaming agent, and whipping time on foam density (FD), foam expansion and foam stability. I optimal design was used. 100 mL prepared sample of bael fruit pulp mixed with different concentrations of GMS (3, 4, 5 and 6 % w/w) and whipped at different whipping times (4, 6, 8 and 10 min).

2.1.1 Foam Expansion

The expansion of the prepared foam was determined by air incorporated into the sample during whipping. It was calculated using the difference in volume of pulp before and after foaming as per the following equation: (Hardy *et al.*, 2017) [13]

$$FE = \frac{V_f - V_{pi}}{V_{pi}} \times 100 \dots\dots 1$$

where,

V_f = Volume of foam, cm^3

V_{pi} = Initial volume of pulp, cm^3

2.1.2 Foam Density

The density of the prepared foam was determined by weighing 50 mL of the mixture in a 50 mL measuring cylinder. The foam transferring was carried out without destroying the foam structure and trapping the air voids was avoided while filling the cylinder (Karim and Wai, 1999b)

[14]. The determinations were done in triplicate for each batch of preparation and the average values were taken. Foam density will be calculated as

$$FD (g/cm^3) = M_f / V_f \dots\dots 2$$

where,

M_f = Mass of foam

V_f = Volume of foam

2.1.3 Foam stability

The stability of the bael fruit pulp foam was determined by estimating the drainage volume. 100 ml of the bael fruit foam was gently transferred into a 250 ml beaker and left undisturbed for 3 h. The drainage volume was measured by gently tilting the beaker and pouring the liquid collected in the bottom of the beaker into a measuring flask. Foam stability will be calculated as (Hardy *et al.*, 2017) [13].

$$FS = (V_{fi} \times t) / V_{cf} \dots\dots 3$$

where,

V_{fi} = Initial foam volume

t = Time interval

V_{cf} = Change in foam volume

2.2 Experimental Design and Statistical Analysis

The ranges of experimental parameters were selected based on preliminary trials. The independent variables considered were: GMS (3-6 g/100 g of pulp) and whipping time (4-10 min). RSM was applied to the experimental data using a commercial statistical package (Design Expert version 8.0.7.1, Statease Inc, Minneapolis, MN) for the generation of response surface plots and optimization of process variables (Patil *et al.* 2014) [16]. The I-Optimal design was used for designing the experiments on foaming using three factors with four levels. A total of 16 runs of different combinations were conducted in this study. The statistical significance of the terms in the regression equation was

examined by analysis of variance (ANOVA). In this study, the optimization of the foaming process was aimed at identifying the optimum levels of three factors which would give minimum foam density, maximum foam expansion and foam stability. Predictive models were used to graphically represent systems. Contour plots of the response variables were utilized applying super imposing surface methodology to select optimum combinations of GMS and whipping time for the production of bael fruit pulp foam. The details of the experimental design used in the present study are given in Table 1.

2.3 Optimization of foamed bael fruits

Numerical and graphical optimization was carried out for the independent variables to obtain the foam with minimum foam density (*i.e.*, maximum foam expansion) and maximum foam stability using Design-Expert software. Kusum *et al.* (2022) Optimized egg powder by foam-mat tray drying using response surface methodology. A conventional graphical method was applied to obtain minimum foam density. Predictive models were used to graphically represent systems. Contour plots of the response variables were utilized applying superimposing surface methodology to select optimum combinations of GMS concentration and whipping time for the production of bael fruit pulp foam.

3. Results and Discussion

The observations for FE, FD and FS with different combinations of the independent variables are presented in Table 1. Analysis of variance showed that the models are highly significant ($p < 0.001$) for both responses. The lack of fit was insignificant in the case of FE, FD and FS, indicating that these models are sufficiently accurate for predicting those responses. The coefficient of determination (R^2) values of both responses was 0.9664, 0.9945 and 0.9387 % indicating high proportion of variability was explained by the data and that the RSM models were adequate. The complete experimental results are given in Table 1.

Table 1: Effect of process variables on FE, FS and FD of foam on bael pulp

Run	Whipping Time min	Foaming Agent %	Foam Density g/cm ³	Foam Expansion %	Foam Stability min
1	6	5	0.54	21.42	0.9667
2	4	6	0.55	21.12	0.9631
3	10	4	0.49	22.4	0.9741
4	10	3	0.53	21.91	0.9692
5	8	4	0.54	21.78	0.9657
6	4	5	0.61	20.67	0.9586
7	4	4	0.65	20.31	0.9511
8	6	5	0.54	21.42	0.9667
9	6	4	0.6	21.02	0.9592
10	8	3	0.59	21.34	0.9627
11	10	6	0.38	22.97	0.9861
12	10	4	0.49	22.4	0.9741
13	8	3	0.59	21.34	0.9627
14	10	6	0.38	22.97	0.9861
15	6	5	0.54	21.42	0.9667
16	4	3	0.69	19.84	0.9479

3.1 Effect of Foaming Process Variables

3.1.1 Foam Density (FD)

FD is commonly used to evaluate whipping properties. The more air incorporated during whipping, the lower the foam density; the more air present in the foam, the higher the whipping ability (Falade *et al.*, 2003) [9]. The density of the

foam varied from 0.38 to 0.69 gcm⁻³ (Table 1). ANOVA indicated that the FD was highly significant at a 0.1% level on linear terms of GMS and whipping time. The effect of GMS and whipping time on foam density is shown in figure 2.

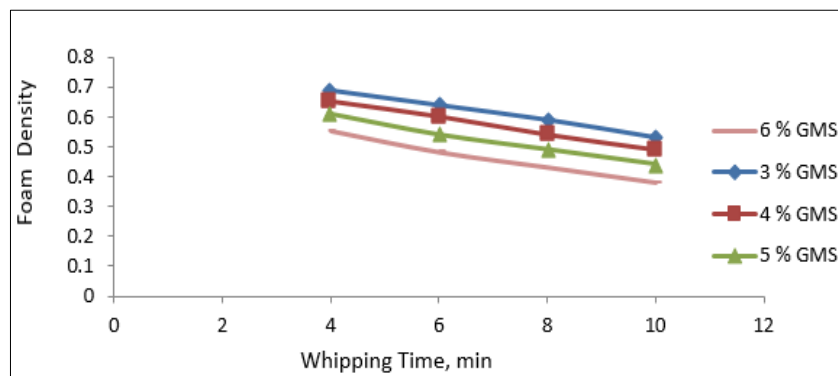


Fig 2: Effect of GMS on whipping time and foam density

Table 2: ANOVA for foam density during foaming of bael fruit

Source	Sum of Squares	Df	Mean Square	F-value	p-value
Model	0.1038	2	0.0519	1165.04	< 0.0001**
A-Whipping time	0.0657	1	0.0657	1474.50	< 0.0001**
B-Foaming agent	0.0452	1	0.0452	1014.74	< 0.0001**
Residual	0.0006	13	0.0032		
Lack of Fit	0.0005	8	0.0001	4.80	0.0503(ns)
Std. Dev.	0.0067				
Mean	0.5438				
C.V. %	1.23				
R ²	0.9945				
Adjusted R ²	0.9936				
Predicted R ²	0.9917				

(** Significant at 1 percent level, ns= non-significant)

3.1.2 Foam Stability (FS)

The stability of any foam can very well be judged by the rate at which the liquid drains from the foam (Kampf *et al.*, 2003) ^[15]. The FS ranged from 0.9511 to 0.9861 % (Table

1). A higher value of foam stability implied a lower water-holding capacity of foam. The effect of GMS and whipping time on foam stability is shown in figure 3.

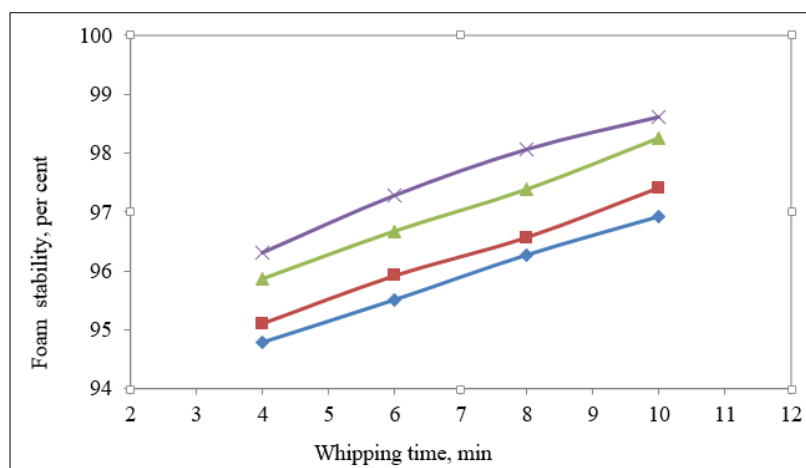


Fig 3: Effect of GMS and whipping time on foam stability

Table 3: ANOVA for foam stability during foaming of bael fruit

Source	SS	df	MS	F-value	p-value
Model	0.0017	2	0.0009	99.60	< 0.0001**
A-Whipping time	0.0014	1	0.0014	157.44	< 0.0001**
B-Foaming agent	0.0005	1	0.0005	53.58	< 0.0001**
Residual	0.0001	13	0.0023		
Lack of Fit	0.0012	8	0.0002	0.1613	0.9878(ns)
Std. Dev.	0.0030				
Mean	0.9660				
C.V. %	0.3056				
R ²	0.9387				
Adjusted R ²	0.9293				
Predicted R ²	0.9205				

(** Significant at 1 percent level, ns= non-significant)

3.1.3 Foam Expansion (FE)

The FE values were found to be in the range of 19.84 to 22.97 % (Table 1) during the present experimental studies. The coefficient of determination (R^2) was found to be 0.9664 which indicated the goodness of fit. The response surface plot from Fig. 5 illustrated that FE increased with an increase in the concentration of SPI. The quadratic terms of

GMS concentration and whipping time were found to be significant at $P < 0.001$ whereas no significance in the interaction and linear terms was observed. This decrease in FE may be associated with the collapse of foam structures with increased WT (Lau and Dickinson, 2005) [18]. The effect of GMS and whipping time on foam expansion is shown in figure 4.

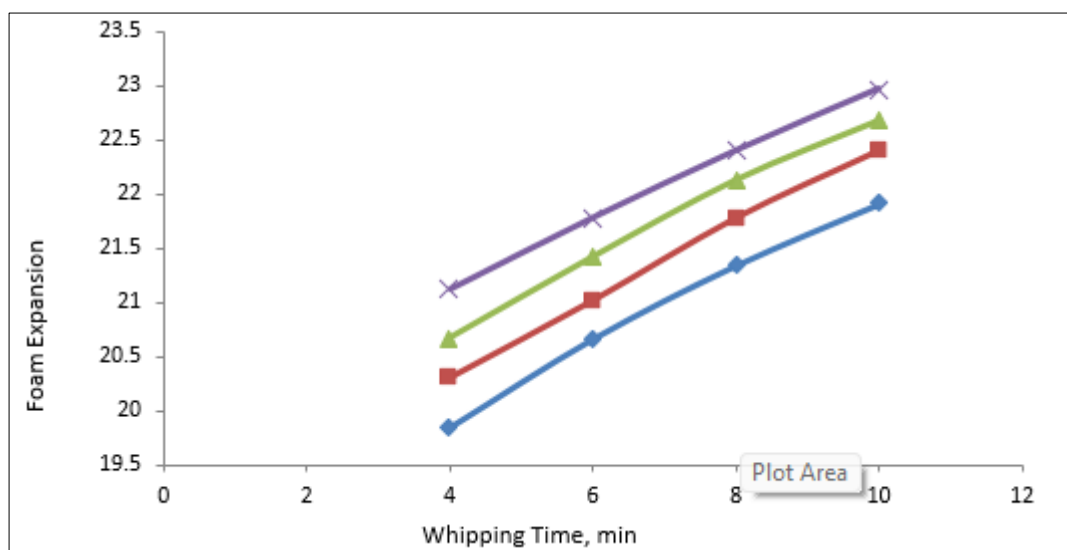
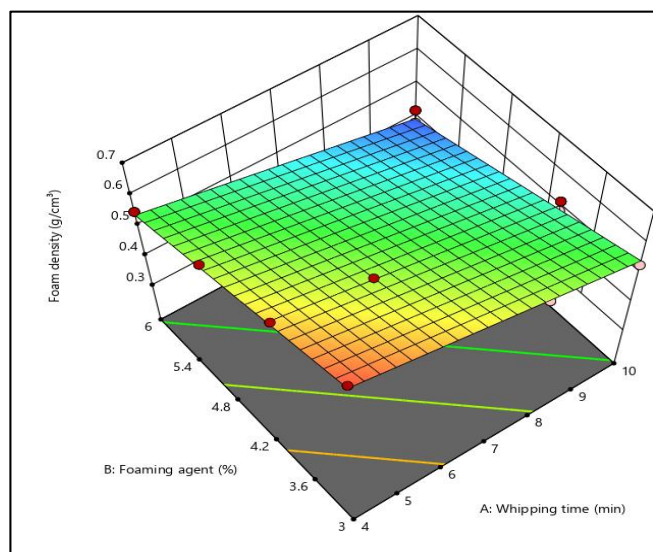


Fig 4: Effect of GMS and whipping time on foam expansion

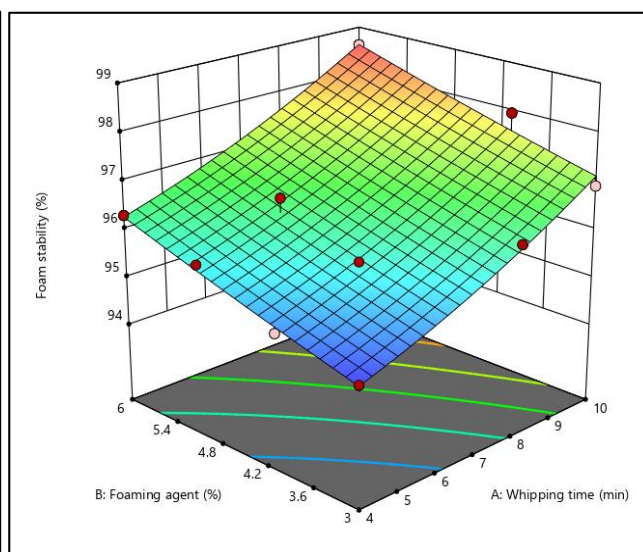
Table 4: ANOVA for foam expansion during foaming of bael fruit

Source	SS	df	MS	F-value	p-value
Model	11.62	2	5.81	187.15	< 0.0001**
A-Whipping time	10.17	1	10.17	327.42	< 0.0001**
B-Foaming agent	2.03	1	2.03	65.47	< 0.0001**
Residual	0.4037	13	0.0311		
Lack of Fit	0.1133	8	0.0142	0.2439	0.9617(ns)
Std. Dev.	0.1762				
Mean	21.48				
C.V. %	0.8205				
R^2	0.9664				
Adjusted R^2	0.9613				
Predicted R^2	0.9556				

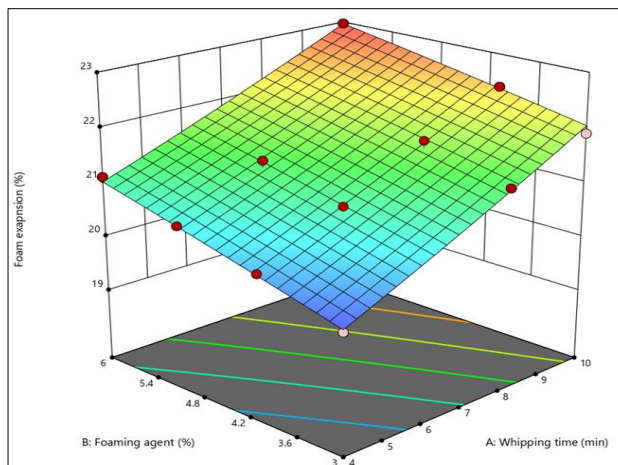
(** Significant at 1 percent level, ns= non-significant)



(a)



(b)



(c)

Fig 5: Contour plots and response surface showing the effect of a GMS and whipping time on (a) foam density, (b) foam stability and (c) foam expansion

Conclusions

Foaming, which is the main process in the expansion of bael fruit pulp was optimized with minimum FD and maximum foam stability so that the foam becomes more stable with maximum expansion. By using quadratic models, the FD, FE and FS of the product were predicted. RSM, the conventional graphic, and desirability function methods were found effective in determining the optimum zone within the experimental region. Optimal conditions for minimum FD and maximum FS and FE corresponded to GMS concentration 6% (w/w) and whipping time 10 min. The desirability of 0.998 was achieved at this optimum point. The FD, FE and FS under optimum conditions of foaming process variables were $0.3795 \pm 0.02 \text{ gcm}^{-3}$, $22.97 \pm 0.02 \%$ and $0.9462 \pm 0.02 \%$, respectively.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgement

Technical support from AICRP on PHET, CIPHET, Ludhiana and Department of Processing and Food Engineering, College of Technology and Engineering, MPUAT, Udaipur, Rajasthan, India is gratefully acknowledged.

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