



RESEARCH ARTICLE

Ultrasonic-assisted extraction of peanut milk-optimisation by using response surface methodology

Siva Sakthi T^{1*}, Amutha S² & Saravanakumar R²

¹Department of Food Science and Nutrition, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, India

²Department of Human Development and Family Studies, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, India

*Correspondence email - sivasakthit1997@gmail.com

Received: 21 September 2025; Accepted: 06 January 2026; Available online: Version 1.0: 31 May 2026

Cite this article: Siva ST, Amutha S, Saravanakumar R. Ultrasonic-assisted extraction of peanut milk-optimisation by using response surface methodology. Plant Science Today. 2026;13(sp2):01–08. <https://doi.org/10.14719/pst.11899>

Abstract

As people become more conscious of the importance of health, ethical concerns and environmental sustainability, demand for plant-based milk beverages is growing worldwide. Peanuts are high in protein, polyunsaturated fatty acids and essential nutrients like vitamin E, magnesium and niacin. They provide a high-energy food source beneficial for overall health and dietary balance. Peanut milk, a nutritious alternative, is rich in plant-based protein, healthy fats and fiber. Both conventional and ultrasonic-assisted extraction (UAEM) methods are used to extract peanut milk, with UAEM offering potential advantages for improving the nutritional profile and quality. The purpose of this research was to determine the best conditions for employing UAEM to extract milk from conventional peanut varieties by analysing milk yield, protein concentration, viscosity and general acceptability. With a 4 hr soaking period, a 20 min sonication time and a 45 °C sonication temperature, the response surface methodology (RSM) was used to optimize the extraction of peanut milk. Key parameters, including milk yield, protein content, viscosity, pH, total soluble solids (TSS), total solids, sedimentation rate, colour value and syneresis, were compared between UAEM and CE methods. Ultrasonic-assisted extraction demonstrated better performance than conventional extraction in terms of milk yield, protein content, viscosity and overall acceptability. Ultrasonic-assisted extraction also improved physicochemical properties, such as pH and TSS, while reducing sedimentation rate and syneresis, demonstrating its superiority for high-quality peanut milk production.

Keywords: optimisation; peanut milk; response surface methodology; ultrasonic assisted extraction

Introduction

In recent years, consumption of plant-based beverages has grown in significance. By 2024, this market sector is expected to reach US\$26 billion globally. Plant-based product consumption is often said to be driven by a desire for a healthy lifestyle, ethical concerns about animal cruelty and environmental concerns. A plant-based diet also has a positive impact on health, as its adherents tend to have healthier lifestyles overall, with a higher level of awareness of their eating and exercise habits, which provide protective factors against chronic diseases (1).

Nowadays, customer concerns about allergies, intolerances and sensitivities to certain components, as well as varying dietary preferences, have led to dietary modifications (2). There is a trend away from animal sources and toward plant sources, driven by the growing global population, the ensuing depletion of natural resources and their connection to sustainability. As a result, plant-based milk substitutes are essential for meeting all these consumer needs. Consequently, there has been a rise in interest in plant-based milk substitutes made from a variety of sources, particularly soy, coconut, almond and oat (3). In the realm of functional and specialty beverages, a relatively new food product category, the demand for plant-based or non-dairy milk is on the rise globally.

Peanut (*Arachis hypogaea* L.) is one of the world's most important legume crops valued for its high nutritional content and economic significance in global agriculture. Global peanut production reaches approximately 50 million metric tons annually. This versatile legume serves as both a food crop and an oilseed, containing approximately 25–28 % protein, 48–50 % fat, 16–18 % carbohydrates, and significant amounts of essential minerals and vitamins (4).

Peanut milk, a plant-based milk alternative, has gained attention as a nutritious and sustainable beverage, particularly among consumers seeking non-dairy options due to lactose intolerance, allergies or ethical preferences. The nutritional profile of peanut milk supports weight control, heart health, and overall well-being. It's an excellent source of dietary fibre, healthy fats, and plant-based protein. It is particularly high in monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA), which have been linked to reduced cholesterol levels and improved cardiovascular health (5).

Among non-thermal processing methods such as gamma radiation, pulsed electric field and pulsed light, ultrasonication is one of the fastest, most versatile and nontoxic (6). Ultrasonication techniques can be applied for homogenisation, emulsification, extraction, cleaning, enzyme inactivation and microbial disinfection (7).

In recent years, the application of ultrasound in non-thermal food processing has seen significant growth in research interest. Ultrasounds are mechanical waves with frequencies greater than the human audible range (16–20 kHz). It can be divided into two frequency ranges. Low-power ultrasound, also known as high-frequency ultrasound, operates at frequencies between 5 and 10 MHz, has low intensity levels (usually less than 1 W cm⁻²), and is mostly used for the diagnostic analysis of food materials (8).

Although UAEM has been extensively studied for soy, oat, and almond milk, limited information is available for peanut milk. This study addresses this gap by systematically optimizing UAEM conditions and evaluating the physicochemical and nutritional quality of peanut milk. RSM was used to optimize key processing variables and the optimized process was validated by direct comparison with conventional Extraction. This integrated approach offers practical insights into process efficiency, product quality and the industrial applicability of ultrasonic-assisted peanut milk production.

This study aims to maximise ultrasonic extraction of plant-based milk from conventional peanut varieties using RSM, thereby exploiting peanut milk for its nutritional and therapeutic qualities. The objective is to produce peanut milk from the selected types with high milk yield, protein content, viscosity and general appeal.

Materials and Methods

The study was conducted at the “Department of Food Science and Nutrition, Community Science College and Research Institute, Tamil Nadu Agricultural University (TNAU), Madurai.” Peanut (traditional variety) was procured from a local farmer in Madurai.

Experimental design and data analysis

Response surface methodology is a powerful optimization tool that uses a structured experimental design to incorporate all independent variables and guide the process. Through this approach, data are gathered and regression analysis is applied to generate precise outputs and predict dependent variables (9). The central composite

design, a non-linear model, is used to manage the variables and derive regression equations from the experimental data (10)

Using a three-factor central composite design, the optimal peanut milk from the traditional peanut variety was created by determining the best predicted values for the creation of peanut milk. We optimized the extraction process for ultrasonically aided plant-based peanut milk using a central composite design of RSM. Soaking time (hr), sonication time (min) and sonication temperature (°C) were taken as independent variables. Milk yield (mL), protein (g), viscosity (cP) and general acceptability were the responses considered.

Soaking time, sonication time and temperature were chosen because they most strongly affect hydration, cavitation, and extraction efficiency in ultrasonic-assisted peanut milk. Other factors, such as amplitude and solvent ratio, were set to optimized levels to ensure reproducibility and prevent adverse effects on milk quality.

Table 1 lists the variables and their respective levels. Using Design-Expert 13, a central composite design was employed. Twenty experimental runs were accomplished in Table 1 for the peanut milk extraction from the traditional variety.

Central composite design experiments were conducted in a randomized order, with each experimental point performed in triplicate as independent runs, and the results expressed as mean ± standard deviation. All processing conditions, raw materials, equipment settings, and analytical procedures were maintained consistently to minimize variability and ensure reproducibility.

Extraction of peanut milk using the ultrasonic-assisted extraction method

In this study traditional peanut varieties were chosen. The selected grains were deshelled, cleaned and washed to remove foreign substances. The UAEM was performed using an ultrasonicator (25 L capacity) operating at a frequency range of 20–25 kHz (Lark Innovative Fine Technologies, Chennai, India). The process parameters soaking time, sonication time and sonication temperature for the preparation of the peanut milk were followed according to experimental design as shown in Tables 1 and 2. Peanuts and water were added in the ratio of

Table 1. Central composite design showing coded (−α to +α) and corresponding actual values of soaking time, sonication time and sonication temperature used for optimisation of ultrasonic-assisted peanut milk extraction

S.No.	Independent variables			Dependent variables			
Run	A: Soaking time	B: Sonication time	C: Sonication temperature	Milk yield ^a	Protein ^a	Viscosity ^a	Overall acceptability ^a
	hr	min	Degree Celsius	%	g/100 mL	cP	
1	6	5	30	77.44	8.36	7.65	8.5
2	6	30	30	77.69	8.57	7.53	8.6
3	2	5	45	79.32	8.36	7.9	7.2
4	4	38.5224	37.5	78.63	8.58	7.66	8.1
5	4	-3.52241	37.5	75.44	8.32	7.5	8.1
6	4	17.5	24.8866	76.54	8.46	7.31	7.7
7	4	17.5	37.5	77.69	8.59	7.94	8.2
8	4	17.5	37.5	77.69	8.59	7.94	8.2
9	4	17.5	50.1134	78.68	8.42	7.86	7.6
10	6	30	45	81.67	8.58	7.94	8.6
11	2	30	45	81.69	8.41	7.9	7.3
12	6	5	45	79.89	8.42	7.63	7.9
13	0.636414	17.5	37.5	80.38	8.32	7.46	7.3
14	4	17.5	37.5	77.69	8.59	7.94	8.2
15	2	5	30	77.53	8.31	7.2	7.1
16	2	30	30	78.63	8.53	7.5	7
17	7.36359	17.5	37.5	81.6	8.35	7.82	8.3
18	4	17.5	37.5	77.69	8.59	7.94	8.2
19	4	17.5	37.5	77.69	8.59	7.94	8.2
20	4	17.5	37.5	77.69	8.59	7.94	8.2

^a values observed in the mean value of the three replicates

1: 6 and it was grinded. The slurry was subjected to conventional and ultra sonic assisted extraction methods. The treated slurry was filtered using muslin cloth and the peanut milk was extracted. Homogenized milk was subjected to homogenization for 5 min and pasteurization at 85 °C for 15 min. Then, they were cooled and packed in both glass and Polyethylene Terephthalate (PET) bottles.

Determination of product responses

Milk yield, protein content, viscosity and overall acceptability were evaluated. Milk yield was measured using a graduated cylinder after Extraction. Protein content was determined from crude nitrogen using the Micro-Kjeldahl method (11). Viscosity was measured using a Brookfield viscometer fitted with spindle No. 61 at 100 rpm. Sensory evaluation was conducted by a panel of 15 semi-trained members (aged 22–35 years), trained to use a 9-point hedonic scale to assess color, aroma, taste, texture and overall acceptability. Coded samples (30 mL) were served at room temperature in randomized order and evaluated in triplicate. All analyses were performed in triplicate and results were expressed as mean $\pm$ standard deviation. Instrumental and sensory data were statistically analyzed to account for experimental and panelist variability.

Statistical analysis

Design-Expert software (v.13.0) was used for data analysis. Response Surface Methodology was applied for model fitting, optimization and interpretation using regression analysis and analysis of variance (ANOVA). Model adequacy was evaluated based on p-values, lack-of-fit tests and coefficients of determination (R^2). The least significant difference (LSD) test ($p < 0.05$) was applied only for post hoc comparisons between conventional and optimized UAEM treatments and was not used to interpret the RSM model. Optimization experiments were conducted in triplicate and the accuracy of the optimized model was validated by comparing predicted and observed values.

Optimization of process parameters

The study of the multifactor, multi-response process required less experimental time and effort than numerical optimization techniques. The various responses were combined into a single desirability function ranging from 0 (totally undesirable) to 1 (fully desirable). Maximum milk yield, protein, viscosity and overall acceptability were selected as dependent variables, while minimal soaking time and sonication duration were selected as independent variables. The process parameters were subjected to ANOVA to determine the linear, interaction and quadratic coefficients at the significance level ($p < 0.05$). The results are displayed in Table 2.

$Y =$

$$\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1 X_1 + \beta_{22} X_2 X_2 + \beta_{33} X_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \text{ (Eqn. 1)}$$

Where Y is a response factor of the extraction yield, protein, viscosity and overall acceptability from the peanut milk extract from the traditional peanut variety and β_0 is a constant. Moreover, β_1 , β_2 and β_3 are linear regression coefficient, β_{11} , β_{22} and β_{33} denote interaction coefficient, β_{12} , β_{13} and β_{23} are quadratic coefficients. The interaction between the chosen dependent and independent variables was displayed using 3D surface plots. The model's shortcomings in the experimental design were assessed using R^2 , adjusted R^2 , anticipated R^2 , and p-values. A higher R^2 value indicates a better model fit. The R^2 value is determined by how well the responses fit the model.

Results and Discussion

Effect of ultrasonic-assisted extraction on milk yield of the peanut milk

In Tables 1 and 2, you can find a thorough account of the experimental conditions and variable interactions for the UAEM of peanut milk. The average milk yield for peanuts was 78.56 %, with a range of 75.44 % to 81.69 %. There is a very small chance that the model's high F-value of 14.02 is due to noise, but the results are still statistically significant. Some model terms, such as B, C and A^2 , were found to be significant ($p < 0.05$); however, other terms were not ($p > 0.05$).

The predicted R^2 (0.4429) differed notably from the adjusted R^2 (0.8604), though an adequate precision value of 12.1170 indicates an adequate signal. This model can be used to navigate the design space. Fig. 1a illustrates 3D plots demonstrating the combined effects of soaking time, sonication time and sonication temperature on milk yield. Under the sonication temperature of 45 °C and the sonication period of 20 min, a milk yield content of 78.27 % was attained. Water helps the active ingredient disperse during ultrasonic assisted milk extraction, increasing the amount of milk produced. A larger yield with less bioactivity loss is achieved by applying ultra sound (12). Extraction yield increased with initial increases in sonication time but declined at longer sonication durations. Numerous studies have demonstrated a linear relationship between sonication time and extraction yield (13). Regarding processing time, the effects of temperature and ultrasonic power on extraction yield are similar. At first, milk supply rises, but as the temperature rises, it gradually falls (14).

Non-significant lack-of-fit values indicate that the models adequately represent the experimental data and are suitable for prediction within the studied range. The lack-of-fit results have been interpreted, confirming model adequacy.

Effect of ultrasonic assisted extraction on protein content of the peanut milk

The ultrasonic-assisted extraction method processing parameters, protein content, and interaction effects on protein content in peanut milk are detailed in Tables 1 and 2. Across 20 treatments, soaking times were 2 hr (5 treatments), 4 hr (10 treatments), and 6 hr (5) and their protein content ranged from 8.31 to 8.53 g 100 mL⁻¹, 8.32 to 8.59 g 100 mL⁻¹ and 8.36 to 8.57 g 100 mL⁻¹, respectively. These results were observed under experimental conditions involving sonication times of 5, 17.5 and 30 min and temperatures of 30 °C, 37.5 °C and 45 °C. The overall peanut milk protein content ranged from 8.31 to 8.59 g 100 mL⁻¹, with an average protein content of 8.48 g 100 mL⁻¹.

The F value of the model was 21.10, which indicates that it is statistically significant, despite the fact that C and AB were not significant ($p > 0.05$). There is a substantial difference ($p < 0.05$) in the p-values of A, B, BC, A^2 , B^2 and C^2 . The R^2 regression coefficient in the experimental scenario was 0.9502, indicating a strong agreement between the expected and observed values. In contrast to the result of 0.9054 for the adjusted R^2 statistic, the value of 0.6113 for the predicted R^2 statistic stood out.

The adequate precision value of 11.8550, which exceeded the recommended threshold of 4, indicates a strong signal-to-noise ratio and confirms the suitability of the model for exploring the experimental design space (Table 2). The interactive effects of soaking time (4 hr), sonication time (20 min) and sonication temperature (45 °C) on the protein content of peanut milk are

Table 2. Regression coefficients and ANOVA estimates for extraction yield, protein, viscosity and overall acceptability of ultrasound-assisted extracted peanut milk from the traditional variety

Factor	DF	Extraction yield (%)			Protein (g/100 mL)			Viscosity (cP/100 mL)			Overall acceptability		
		Coefficient Estimate	Sum of squares	F value	p - value	Coefficient Estimate	Sum of squares	F-value	p - value	Coefficient t Estimate	Sum of squares	F-value	p - value
Model	9	77.67	51.72	14.02	0.0001	8.59	0.2292	21.20	<0.0001	7.94	0.9823	10.30	0.0006
Linear													
A	1	0.1151	0.1809	0.4412	0.5216	0.0271	0.0100	8.36	0.0161	0.0626	0.0536	5.06	0.0483
B	1	0.7956	8.64	21.08	0.0010	0.0789	0.0850	70.72	<0.0001	0.0556	0.0422	3.98	0.0740
C	1	1.09	16.21	39.53	<0.0001	-0.0049	0.0003	0.2758	0.6109	0.1768	0.4270	40.29	<0.0001
Interactions													
AB	1	-0.1800	0.2592	0.6321	0.4450	0.0125	0.0013	1.04	0.3318	-0.0138	0.0015	0.1427	0.7135
AC	1	0.1975	0.3120	0.7610	0.4035	0.0175	0.0024	2.04	0.1838	-0.0888	0.0630	5.95	0.0350
BC	1	0.3500	0.9800	2.39	0.1532	-0.0275	0.0060	5.04	0.0487	0.0162	0.0021	0.1993	0.6648
Quadratic													
A²	1	1.30	24.39	59.47	<0.0001	-0.0806	0.0937	77.96	<0.0001	-0.0902	0.1173	11.07	0.0077
B²	1	-0.0974	0.1368	0.3337	0.5763	-0.0400	0.0230	19.15	0.0014	-0.1114	0.1789	16.88	0.0021
C²	1	0.1059	0.1615	0.3938	0.5444	-0.0435	0.0273	22.69	0.0008	-0.1097	0.1733	16.35	0.0023
Lack of fit	5		4.10				0.0120				0.1060		
Mean±SD			78.56±0.64				8.48±0.03				7.72±0.10		
R²			0.9265				0.9502				0.9026		
Adjusted R²			0.8604				0.9054				0.8150		
Predicted R²			0.4429				0.6113				0.1647		
CV			0.8151				0.40				1.33		

The *p*-values indicate the significance level of each coefficient. A, B and C indicate that soaking time, sonication time and sonication temperature, respectively. *p*-values < 0.005 are indicated as a significant effect of the independent factor on the response variable at the 5 % level. Abbreviations: CV: Critical value; df: degree of freedom; SD: standard deviation.

illustrated in the three-dimensional response surface plots (Fig. 1b).

Ultrasonic cavitation produces intense localized mechanical forces, including shear, microjets and turbulence, which disrupt secondary and tertiary protein structures by breaking non-covalent interactions. In peanut milk, these effects cause partial protein unfolding, increased exposure of hydrophobic groups and reduced aggregate size, leading to changes in functional properties such as solubility and emulsification. This mechanism explains the observed alterations in protein content and functionality following ultrasound treatment.

Ultrasonic processing has been reported to enhance the nutritional value and bioactive properties of plant-based milk. In soybean milk, ultrasonication at 400 W and 25 kHz for 16 min reduced trypsin inhibitor activity by 7.4 % and increased protein digestibility by 52 % (15). Similarly, the protein content of coconut milk increased from 5.18 to 6.15 g 100 mL⁻¹ after sonication, likely due to cavitation-induced denaturation of lipoproteins (16). In agreement with these findings, the present study observed an increase in protein content of coconut milk from 5.18 to 6.51 g 100 mL⁻¹ following ultrasonication. Previous studies have also shown that ultrasonication at 20 kHz denatures whey proteins in both whole and skim milk (17), supporting the role of cavitation in altering protein structure and availability.

Non-significant lack-of-fit values indicate that the models adequately represent the experimental data and are suitable for prediction within the studied range. The lack-of-fit results have been interpreted, confirming model adequacy.

Effect of ultrasonic-assisted extraction on viscosity content of the peanut milk

The experimental conditions for UAEM processing of peanut milk and their variable interactions are detailed in Tables 1 and 2. The viscosity of ultrasound-assisted extracted peanut milk ranges from 7.2 to 7.94 cP 100 mL⁻¹. The average viscosity content of the peanut milk from the traditional variety was 7.72 cP 100 mL⁻¹.

The model's F value of 10.30 indicates statistical significance, with a very small 0.06 % chance that noise is the explanation. A model term is considered significant if its p-value is less than 0.05. A, C, AC, A², B and C² are these terms. However, if a term's p-value was more than 0.1000, it was deemed non-significant. The regression coefficient (R²) of 0.8150 indicated that the actual results closely matched the expected values. The adjusted R² (0.8150) and the predicted R² (0.1647), however, differed significantly by more than 0.2. The recommended threshold of 4 was exceeded by a factor of 2.4 by the value of 9.5142, which measures the signal-to-noise ratio. This implies a reliable signal for moving across the experimental design space.

The combined effects of soaking time, sonication time, and sonication temperature on viscosity are illustrated in the three-dimensional response surface plots (Fig. 1c). A soaking time of 4 h, sonication time of 20 min and sonication temperature of 45 °C resulted in the highest viscosity (7.53 cP 100 mL⁻¹) for peanut milk prepared from the conventional variety.

The apparent viscosity of the milk increased as temperature and ultrasound amplitude increased; this may be due to the denaturation of heat-sensitive whey proteins. Increased viscosity of continuous phase and volume fractions of gel and higher disulfide binding capacity associated with water and whey proteins; disruption of the third and fourth structures of casein micelles,

followed by an increase in available caseins and the formation of a stronger network and better particle interactions (18).

Ultrasonic treatment increased the viscosity of millet milk with increasing sonication time, rising from 11.60 ± 0.18 to 16.59 cP, likely due to internal heat accumulation during prolonged sonication. Finger millet-based beverages have been reported to exhibit viscosities ranging from 2.43 to 26.40 cP (19). Increased viscosity in peanut milk enhances texture and mouthfeel, making it more comparable to conventional dairy milk. Plant-based milks with appropriate thickness and flow behavior are generally preferred, thereby improving sensory quality and overall palatability.

The observed difference between R² and predicted R², particularly in the viscosity model, may be due to the model capturing minor experimental variability or noise, leading to slightly optimistic fitting (overfitting) for the experimental dataset. However, diagnostic checks, including residual analysis, lack-of-fit tests, and cross-validation, confirmed that the model is statistically adequate and reliable for prediction within the studied range. Non-significant lack-of-fit values indicate that the models adequately represent the experimental data and are suitable for prediction within the studied range. The lack-of-fit results have been interpreted, confirming model adequacy.

Effect of ultrasonic-assisted extraction on the overall acceptability of the peanut milk

Twenty treatments showed an average overall acceptance of 7.9 for UAEM peanut milk, ranging from 7 to 8.6. Factors A, A², and C² significantly affected viscosity content ($p > 0.05$), as indicated by the statistically significant model ($F=11.90$). Although the adjusted R² of 0.8377 is significantly higher than the predicted R² of 0.3448, the model is still well-fitting, as evidenced by the R² of 0.9146. With an adequate precision ratio of 11.37, the model is clearly suitable for exploring the design space and also provides a solid signal. The combined effects of soaking duration (4 hr), sonication time (20 min) and sonication temperature (45 °C) on overall acceptability are illustrated in the 3D plots in Fig. 1d.

Sedimentation qualities of plant-based milk are recognized as significant functional qualities, among others, including viscosity, colour, appearance, turbidity and flavour. It will determine the overall acceptability of the non-dairy plant-based milk on the market (20). A kinnow whey-based beverage that had been sonicated for 15 min had the highest overall acceptance. It was revealed that among several treatments, a beverage sonicated for 15 min can be stored at refrigerated temperatures for up to 3 months without the use of any preservatives (21).

The findings demonstrate that RSM-optimized UAEM offers statistically significant and practically relevant improvements over conventional Extraction, confirming its potential as an efficient and scalable technology for high-quality peanut milk production.

The ANOVA tables have been critically interpreted by identifying the most influential model terms. Linear effects of soaking time (A), sonication time (B) and sonication temperature (C), along with significant quadratic terms (A², B², C²), were found to predominantly govern milk yield, protein content, viscosity and overall acceptability due to their direct influence on hydration, cavitation intensity, and thermal effects during Ultrasonic-Assisted Extraction. Non-significant lack-of-fit values indicate that the models adequately represent the experimental data and are suitable for prediction within the studied range. The lack-of-fit results have been

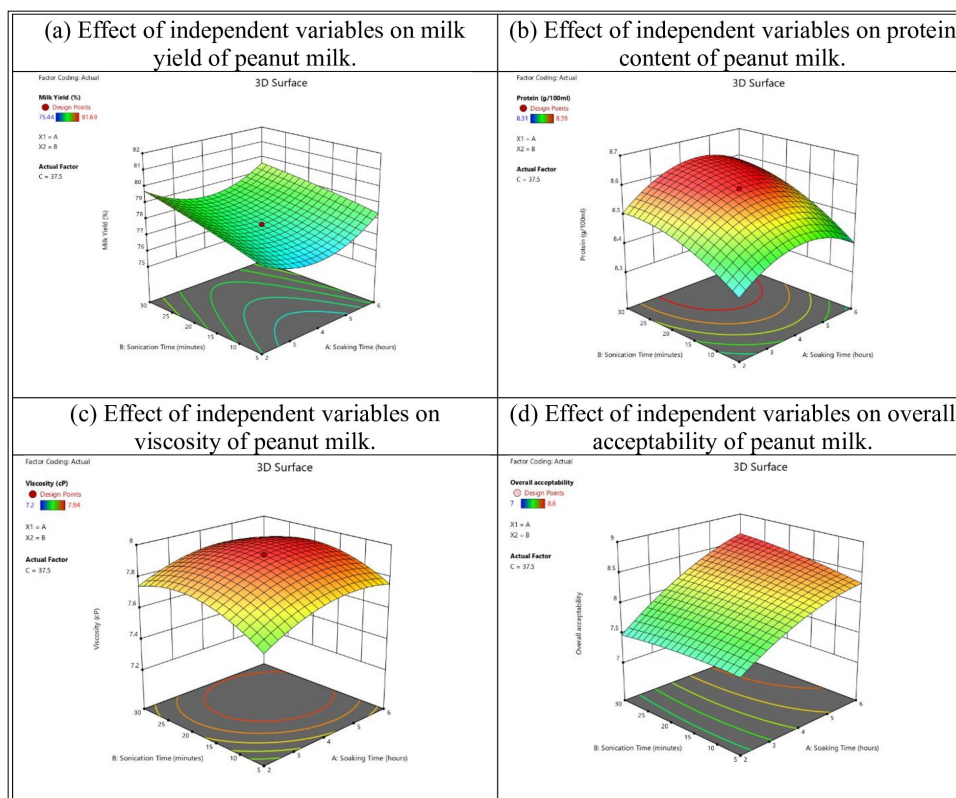


Fig. 1. Response surface plots for milk yield, protein, viscosity and overall acceptability content from UAEM peanut (traditional variety) milk. a: Effect of independent variables on milk yield of peanut milk; b: Effect of independent variables on protein content of peanut milk; c: Effect of independent variables on viscosity content of peanut milk; d: Effect of independent variables on the overall acceptability of peanut milk.

interpreted, confirming model adequacy.

Comparisons of physicochemical characteristics of Conventional and ultrasonic-assisted extraction

The comparative analysis of (CE) and UAEM of peanut milk highlights notable differences in physicochemical parameters, suggesting the superior efficiency of UAEM in enhancing product quality (Table 3). The pH values for both CE (6.6) and UAEM (6.5) peanut milk were similar, indicating no significant changes in acidity level due to extraction methods. However, UAEM peanut milk exhibited higher total soluble solids (TSS) (7.9°C Brix) and total solids (13.24 %), reflecting improved extraction efficiency and nutrient retention.

Ultrasonic-Assisted Extraction significantly improved viscosity (6.94 cP compared to 5.92 cP), suggesting better homogenization and a creamier texture, likely due to ultrasonic-induced breakdown of large fat globules and proteins. Specific gravity was marginally higher in UAEM (1.032) than in CE (1.030), consistent with its higher solids content. The colour parameters (L^* , a^* , b^*) indicated that UAEM milk had a brighter appearance ($L^* = 90.85$), slightly higher redness ($a^* = 0.89$) and lower yellowness ($b^* = 13.68$) than CE, which may contribute to improved visual appeal.

Ultrasonic-Assisted Extraction demonstrated significantly lower sedimentation rate (0.34 g/40 mL) and syneresis (13.78 mL hr⁻¹) than CE, indicating better physical stability and reduced phase separation. These improvements in UAEM peanut milk are attributed to the ultrasonic cavitation process, which enhances emulsification and improves the uniform distribution of soluble solids. Overall, UAEM improved the nutritional and sensory properties and enhanced the physical stability of peanut milk,

making it a promising method for producing high-quality plant-based beverages.

Sonicated peanut milk samples showed higher TSS, rising from 9.1°Brix in untreated samples to 11-12° Brix. Processed peanut milk samples showed a slight increase in pH compared to untreated samples. Titratable acidity decreased with increasing cavitation intensity in ultrasonically treated samples (22). Processed peanut milk samples showed a slight increase in pH compared to untreated samples. Additionally, titratable acidity decreased with increasing cavitation intensity in both ultrasound and hydrodynamic cavitation treatments, likely due to changes in particle charge induced by cavitation.

The TSS was higher in sonicated samples, rising from 9.1 °Brix in untreated samples to 11-12° Brix. By contrast, the high-temperature short-time (HTST) treatment produced a Brix of 14°, likely due to either water absorption or partial boiling of peanut particles at high temperatures, which led to their expansion. As a result, there were notable differences among the therapies.

Mechanistic explanations of ultrasonic cavitation emphasize that bubble formation and collapse generate microjets, shear forces, and localized heating, thereby disrupting peanut cell walls, enhancing mass transfer, and promoting the release of proteins and lipids into the aqueous phase. This mechanistic insight explains the observed improvements in extraction efficiency, viscosity, stability, and sensory quality of UAEM peanut milk.

Although the numerical differences appear modest, the statistically significant improvements ($p < 0.05$) observed with UAEM are practically relevant in plant-based milk systems, contributing to enhanced nutritional value, functional properties, and overall product quality.

Table 3. Comparison of physicochemical properties of ultrasonic-assisted extraction and control peanut milk

Parameters	CE ^a	UAEM ^b	P value	% change
pH	6.6 ± 0.17	6.5 ± 0.04	0.002	1.52
TSS (°Bx)	7.5 ± 0.20	7.9 ± 0.13	0.003	17.23
Acidity (%)	0.23 ± 0.004	0.31 ± 0.00	0.001	34.78
Viscosity (cP)	5.92 ± 0.05	6.94 ± 0.08	0.002	17.23
Specific Gravity	1.030 ± 0.007	1.032 ± 0.02	0.003	0.19
L *	88.63 ± 0.00	90.85 ± 1.97	0.007	2.51
a *	0.74 ± 0.012	0.89 ± 0.02	0.009	20.27
b *	14.49 ± 0.019	13.68 ± 0.01	0.002	15.64
Sedimentation Rate (g/40 mL)	0.87 ± 0.01	0.34 ± 0.004	0.005	60.92
Syneresis (mL/hr)	15.25 ± 0.33	13.78 ± 0.32	0.003	9.64
Total solids (%)	12.96 ± 0.37	13.24 ± 0.288	0.002	2.160

Values mentioned as mean ± standard deviation of three replicate analysis (n = 3)

The treatments are significantly differed at $p < 0.05$

Abbreviations: CEM: Conventional extraction method, UAEM: Ultrasonic assisted extraction method

a) Control without ultrasonic treatment

b) optimised value obtained from the soaking time (4 hr), sonication time (20 min) and sonication temperature (45 °C).

c) values are approximate and not mentioned with standard deviation

d) Bx- Brix, cP – Centipose

Conclusion

The comparative analysis of conventional methods and UAEM of peanut milk, optimised using RSM under conditions of 4 hr soaking time, 20 min sonication time and 45 °C sonication temperature, revealed that the UAEM method outperformed the conventional approach. Ultrasonic-Assisted Extraction yielded higher milk yield, protein content, viscosity and overall acceptability. Physicochemical characteristics analysis further demonstrated the superiority of UAEM, with significantly improved pH, TSS and total solids, along with reduced sedimentation rate and syneresis. These findings underscore the efficacy of UAEM as a superior extraction technique for peanut milk production.

Acknowledgements

The authors express their sincere gratitude to DST-SHRI for funding the study on which the research paper is based.

Authors' contributions

SST prepared the original draft. SST, AS and SKR contributed to conceptualisation, data curation, formal analysis, investigation, methodology, resource provision and writing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The Authors do not have any conflicts of interest to declare.

Ethical issues: None

References

- Lawrence AS, Huang H, Johnson BJ, Wycherley TP. Impact of a switch to plant-based foods that visually and functionally mimic animal-source meat and dairy milk for the Australian population-a dietary modelling study. *Nutrients*. 2023;15(8):1825. <https://doi.org/10.3390/nu15081825>
- Reyes-Jurado F, Soto-Reyes N, Dávila-Rodríguez M, Lorenzo-Leal AC, Jiménez-Munguía MT, Mani-López E, et al. Plant-based milk alternatives: types, processes, benefits, and characteristics. *Food Rev Int*. 2023;39(4):2320–51. <https://doi.org/10.1080/87559129.2021.1952421>
- Abagoshu NA, Ibrahim AM, Teka TA, Mekonnen TB. Effect of soybean varieties and processing methods on nutritional and sensory properties of soymilk. *J Food Process Preserv*. 2017;41(4):e13014. <https://doi.org/10.1111/jfpp.13014>
- Archana A, Verma P, Pandey N. Impact of inadequate concentration of boron in seed storage proteins content in oilseed crops. In: Lopez JCL, editor. *Grain and seed proteins functionality*. London: IntechOpen; 2021. <https://doi.org/10.5772/intechopen.95873>
- Arya SS, Salve AR, Chauhan S. Peanuts as functional food: a review. *J Food Sci Technol*. 2016;53:31–41. <https://doi.org/10.1007/s13197-015-2007-9>
- Kentish S, Ashokkumar M. The physical and chemical effects of ultrasound. In: Feng H, Barbosa-Canovas G, Weiss J, editors. *Ultrasound technologies for food and bioprocessing*. New York: Springer; 2011. p. 1-12. https://doi.org/10.1007/978-1-4419-7472-3_1
- O'Donnell CP, Tiwari BK, Bourke P, Cullen PJ. Effect of ultrasonic processing on food enzymes of industrial importance. *Trends Food Sci Technol*. 2010;21(7):358–67. <https://doi.org/10.1016/j.tifs.2010.04.007>
- Karki B, Lamsal BP, Jung S, van Leeuwen JH, Pometto AL 3rd, Grewell D, Khanal SK. Enhancing protein and sugar release from defatted soy flakes using ultrasound technology. *J Food Eng*. 2010;96(2):270–78. <https://doi.org/10.1016/j.jfoodeng.2009.07.023>
- Said KA, Amin MA. Overview on the response surface methodology (RSM) in extraction processes. *J Appl Sci Process Eng*. 2015;2(1):8–17. <https://doi.org/10.33736/jaspe.161.2015>
- Sadhukhan B, Mondal NK, Chattoraj S. Optimisation using central composite design (CCD) and the desirability function for sorption of methylene blue from aqueous solution onto Lemna major. *Karbala Int J Mod Sci*. 2016;2(3):145–55. <https://doi.org/10.1016/j.kijoms.2016.03.005>
- AOAC. Official methods of analysis. 17th ed. Gaithersburg, MD: Association of Official Analytical Chemists; 2000.
- Mehta N, S J, Kumar P, Verma AK, Umaraw P, Khatkar SK, et al. Ultrasound-assisted Extraction and the encapsulation of bioactive components for food applications. *Foods*. 2022;11(19):2973. <https://doi.org/10.3390/foods11192973>
- Raza A, Li F, Xu X, Tang J. Optimization of ultrasonic-assisted extraction of antioxidant polysaccharides from the stem of *Trapa quadrispinosa* using response surface methodology. *Int J Biol*

- Macromol. 2017;94(Pt A):335–44. <https://doi.org/10.1016/j.ijbiomac.2016.10.033>
14. Pan G, Yu G, Zhu C, Qiao J. Optimization of ultrasound-assisted extraction (UAE) of flavonoid compounds from hawthorn seed. *Ultrason Sonochem.* 2012;19(3):486–90. <https://doi.org/10.1016/j.ultsonch.2011.11.006>
 15. Vanga SK, Wang J, Raghavan V. Effect of ultrasound and microwave processing on the structure, *in-vitro* digestibility and trypsin inhibitor activity of soymilk proteins. *LWT.* 2020;131(2):109708. <https://doi.org/10.1016/j.lwt.2020.109708>
 16. Indu C, Thangavel K, Amirtham D. Influence of ultrasonication on stability and physicochemical properties of coconut milk. *J Pharmacogn Phytochem.* 2019;8(3):3565–70.
 17. Villamiel M, de Jong P. Influence of high-intensity ultrasound and heat treatment in continuous flow on fat, proteins, and native enzymes of milk. *J Agric Food Chem.* 2000;48(2):472–78. <https://doi.org/10.1021/jf990181s>
 18. Maran JP, Priya B, Al-Dhabi NA, Ponmurugan K, Moorthy IG, Sivarajasekar N. Ultrasound-assisted citric acid mediated pectin extraction from industrial waste of *Musa balbisiana*. *Ultrason Sonochem.* 2017;35(Pt A):204–09. <https://doi.org/10.1016/j.ultsonch.2016.09.019>
 19. Shunmugapriya K, Kanchana S, Maheswari TU, Saravanakumar R, Vanniarajan C. Optimization of the process parameters for extraction of millet milk. *Int J Biochem Res Rev.* 2020;29:39–47. <https://doi.org/10.9734/ijbcr/2020/v29i430184>
 20. Sarangapany AK, Murugesan A, Annamalai AS, Balasubramanian A, Shanmugam A. An overview on ultrasonically treated plant-based milk and its properties: a review. *Appl Food Res.* 2022;2(2):100130. <https://doi.org/10.1016/j.afres.2022.100130>
 21. Siddique F, Hussain A, Noreen S, Arif MR, Yaqub S, Batool SA, et al. Impact of different processing techniques (chemical, heating and sonication) on physicochemical and microbial characterization of kinnow-whey based beverage. *Discover Food.* 2023;3:18. <https://doi.org/10.1007/s44187-023-00060-w>
 22. Salve AR, Pegu K, Arya SS. Comparative assessment of high-intensity ultrasound and hydrodynamic cavitation processing on physico-chemical properties and microbial inactivation of peanut milk. *Ultrason Sonochem.* 2019;59:104728. <https://doi.org/10.1016/j.ultsonch.2019.104728>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.