Food Processing and Preservation Journal

Print ISSN: 2423-3544
Online ISSN: 2423-3803

Gorgan University of Agricultural Sciences and Natural Resources

Iranian Association of Food Scientists and Technologists

Protein extraction from sesame waste using ohmic technology and optimization of its foaming capacity and stability

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Article Info

Article type:
Research Full Paper

Article history:
Received: 2025-05-13
Revised: 2025-08-28
Accepted: 2025-09-21

Keywords:
Optimization
Sesame waste protein
Foam stability
Foam capacity Sensory parameters

ABSTRACT

Background and Objective: With the increasing global population, limited availability of animal protein sources, and growing demand for sustainable protein alternatives, the use of plant-based proteins has gained more importance, particularly in developing countries. Sesame meal is a promising source of plant protein due to its high protein content, balanced amino acid profile, and the presence of essential amino acids such as methionine and tryptophan. In this study, protein was extracted from dehulled sesame meal through ohmic heating, and its functional properties, including foaming capacity and foam stability, was optimized using response surface methodology (RSM).

Materials and Methods: Sesame meal was ground and passed through a 30-mesh sieve to obtain uniform particles. The samples were defatted using hexane and then dried at ambient temperature. Protein extraction was conducted using an ohmic heating system. The effect of three independent variables—pH (9–11), ammonium sulfate concentration (0.1–0.3% w/v), and voltage (25–35 V)—were investigated under constant frequency (50 Hz) and constant temperature (30 °C). A constant solid to solvent ratio of 1:10 was maintained throughout all experiments. The experimental design followed a Central Composite Design (CCD) under RSM, comprising 32 runs including 6 replicates at the central point. After ohmic treatment, the samples were evaluated to measure the functional properties including foaming capacity and foam stability (after 60 min). For this purpose, 250 mg of protein sample was dissolved in 25 ml of distilled water, adjusted to pH of 7, and mixed for 1 minute using a stirrer. Foam volume was recorded at the formation time and after 60 minutes, and both foaming capacity and foam stability were calculated. Data analysis was performed using Design Expert software and the accuracy of the model was checked with Student’s t-test at a significance level of 0.05.

Results: Analysis of variance showed that the quadratic model was significant for both responses ($p < 0.0001$). The variables pH and voltage had a significant effect on foaming capacity, while ammonium sulfate concentration was not significant. However, all interaction effects between the three variables were statistically significant for both responses. Maximum foaming capacity was observed under high alkaline pH, low voltage, and high salt concentration, whereas maximum foam stability occurred under high voltage, high salt concentration, and low pH. The R^2 value for the foaming capacity model was 0.9440 and for foam stability was 0.9353.

Conclusion: The statistical model was highly accurate and reliable, and the suggested optimal values were pH of 10, ammonium sulfate concentration of 0.3%, and voltage 25 of V. Comparison of the predicted results with the experimental values showed no significant difference ($p > 0.05$). As a result, protein extracted from sesame meal by ohmic heating has favorable foaming properties and can be used as a foaming agent in the production of food products such as desserts, plant-based creams, and processed breads. This extraction method is considered an efficient and sustainable method for utilizing agricultural waste in the food industry.

Cite this article: Keshani, M., Zamindar, N., Lakzadeh, L., Goli, M. 2025. Protein extraction from sesame waste using ohmic technology and optimization of its foaming capacity and stability. *Food Processing and Preservation Journal*, 17(3), 97-110.

10.22069/fppj.2025.23619.1879

Publisher: Gorgan University of Agricultural Sciences and Natural Resources

فرآوری و نگهداری مواد غذایی
شاپا چاپی: ۳۵۴۴-۲۴۲۳
شاپا الکترونیکی: ۳۸۰۳-۲۴۲۳

استخراج پروتئین از ضایعات کنجد با استفاده از فناوری اهمیک و بهینه‌سازی ظرفیت و پایداری کف آن

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اطلاعات مقاله	چکیده

نوع مقاله:
مقاله کامل علمی-پژوهشی

تاریخ دریافت: ۱۴۰۴/۰۲/۲۳
تاریخ ویرایش: ۱۴۰۴/۰۶/۰۶
تاریخ پذیرش: ۱۴۰۴/۰۶/۳۰

واژه‌های کلیدی:
بهینه‌سازی
پروتئین ضایعات کنجد
پایداری کف
ظرفیت کف

سابقه و هدف :با توجه به افزایش جمعیت جهان، محدودیت دسترسی به منابع پروتئین حیوانی و تقاضای روزافزون برای جایگزین‌های پروتئینی پایدار، استفاده از پروتئین‌های گیاهی، به ویژه در کشورهای در حال توسعه، اهمیت بیشتری یافته است. کنجاله کنجد (Sesame meal) به دلیل محتوای پروتئینی بالا، پروفایل اسید آمینه متعادل و وجود اسیدهای آمینه ضروری نظیر متیونین و تریپتوفان، منبعی نویدبخش برای پروتئین گیاهی محسوب می‌شود. در این پژوهش، پروتئین از کنجاله کنجد پوست‌گیری شده با استفاده از گرمایش اهمیک استخراج گردید و ویژگی‌های عملکردی آن، شامل ظرفیت کف‌کنندگی و پایداری کف، با استفاده از روش سطح پاسخ (RSM) بهینه‌سازی شد.

مواد و روش‌ها :کنجاله کنجد آسیاب شده و جهت دستیابی به ذرات یکنواخت از الک مش ۳۰ عبور داده شد. نمونه‌ها با استفاده از حلال هگزان چربی‌گیری شده و سپس در دمای محیط خشک شدند. استخراج پروتئین با استفاده از سیستم گرمایش اهمیک انجام گرفت. اثر سه متغیر مستقل شامل pH (در دامنه ۹ تا ۱۱)، غلظت سولفات آمونیوم (۱/۰ تا ۳/۰ درصد وزنی/حجمی) و ولتاژ (۲۵ تا ۳۵ ولت) در فرکانس ثابت (۵۰ هرتز) و دمای ثابت (۳۰ درجه سانتی‌گراد) مورد بررسی قرار گرفت. نسبت جامد به حلال در تمامی آزمایش‌ها ثابت و برابر ۱ به ۱۰ در نظر گرفته شد. طراحی آزمایش بر اساس طرح مرکب مرکزی (CCD) در قالب روش سطح پاسخ (RSM) انجام شد که شامل ۳۲ اجرا (با ۶ تکرار در نقطه مرکزی) بود. پس از تیمار اهمیک، نمونه‌ها جهت اندازه‌گیری ویژگی‌های عملکردی شامل ظرفیت کف‌کنندگی و پایداری کف (پس از ۶۰ دقیقه) ارزیابی شدند. بدین منظور، ۲۵۰ میلی‌گرم نمونه پروتئین در ۲۵ میلی‌لیتر آب مقطر حل شد، pHآن روی ۷ تنظیم گردید و به مدت ۱ دقیقه با همزن مخلوط شد. حجم کف در زمان تشکیل و پس از ۶۰ دقیقه ثبت گردید و هر دو فاکتور ظرفیت و پایداری کف محاسبه شدند. تحلیل داده‌ها با نرم‌افزار Design Expert انجام شد و دقت مدل با

آزمون-t استیودنت در سطح معنی‌داری ۰٫۵ بررسی گردید.

یافته‌ها: آنالیز واریانس نشان داد که مدل درجه دوم برای هر دو پاسخ معنی‌دار بود ($p < 0.0001$). متغیرهای pH و ولتاژ تأثیر معنی‌داری بر ظرفیت کف‌کنندگی داشتند، در حالی که غلظت سولفات آمونیوم معنی‌دار نبود. با این حال، تمام اثرات متقابل بین سه متغیر برای هر دو پاسخ از نظر آماری معنی‌دار بودند. بیشترین ظرفیت کف‌کنندگی در شرایط pH قلیایی بالا، ولتاژ پایین و غلظت نمک بالا مشاهده شد، در حالی که بیشترین پایداری کف در ولتاژ بالا، غلظت نمک بالا و pH پایین رخ داد. مقدار ضریب تبیین (R^2) برای مدل ظرفیت کف‌کنندگی برابر با ۰.۹٤٤ و برای پایداری کف ۰.۹۳۵۳ به دست آمد.

نتیجه‌گیری: مدل آماری از دقت و قابلیت اطمینان بالایی برخوردار بود و مقادیر بهینه پیشنهادی شامل pH برابر ۱۰، غلظت سولفات آمونیوم ۰٫۳ درصد و ولتاژ ۲۵ ولت تعیین شد. مقایسه نتایج پیش‌بینی شده با مقادیر تجربی هیچ اختلاف معنی‌داری را نشان نداد ($p > 0.05$). در نتیجه، پروتئین استخراج شده از کنجاله کنجد توسط گرمایش اهمیک دارای خواص کف‌کنندگی مطلوبی است و می‌تواند به عنوان عامل کف‌کننده در تولید محصولات غذایی نظیر دسرها، خامه‌های گیاهی و نان‌های فرآوری شده مورد استفاده قرار گیرد. این روش استخراج، روشی کارآمد و پایدار برای بهره‌برداری از ضایعات کشاورزی در صنایع غذایی محسوب می‌شود.

استناد: کشانی، مریم؛ زمین‌دار، نفیسه؛ لک‌زاده، لیلا؛ گلی، محمد. (۱٤۰٤). استخراج پروتئین از ضایعات کنجد با استفاده از فناوری اهمیک و بهینه‌سازی ظرفیت و پایداری کف آن. *فرآوری و نگهداری مواد غذایی*، ۱۷(۳)، ۱۱۰-۹۷.

10.22069/fppj.2025.23619.1879

ناشر: دانشگاه علوم کشاورزی و منابع طبیعی گرگان

Introduction

In today's world, plant-based proteins are increasingly important in human nutrition, particularly in developing nations where average protein intake is less than the body's minimum requirements (Kanu et al., 2007). The limited availability of animal-derived protein sources has increased efforts to discover new protein sources with beneficial functional properties and nutritional value (Egorova et al., 2017). Additionally, researchers suggest that plant-based proteins offer a more cost-effective alternative to animal-based proteins (Hamedanian & Zamindar; Muhamyankaka et al., 2013).

Among plant-based protein sources, sesame (*Sesamum indicum* L.) is an erect and annual herb with seeds known as the oldest oilseed plants. Sesame seeds cultivated for hundreds of years by the people of Africa and Asia. Sesame oil is widely used in food production and numerous industries today. The global production of sesame has accelerated significantly over time, from about 2.5 million tons in 1997 to 6.5 million tons in 2019 (Mustafa & Hüseyin, 2023).

Sesame seeds are remarkably rich in oil and protein. Sesame seeds comprise 45.46-59.28% oil, 21.43-25.77% protein, 2.70-5.10% moisture, 2.89-5.44% ash, 3.20-7.31% fiber, and 4.33-19.33% carbohydrates (Achouri et al., 2012; Fasuan et al., 2018). The chemical composition of sesame seeds varies depending on several factors including degree of maturity, genetics, analytical strategies, surrounding environment, harvest time, and climate conditions (Onsaard, 2012).

Sesame flour is a byproduct of the oil extraction, whose protein content can reach 50% depending on the extraction technique. Sesame protein isolates or concentrates are generally prepared using isoelectric precipitation, consisting of 80% α-globulin and 20% beta-globulin. Dehulled sesame meal includes high amounts of methionine and tryptophan, distinguishing it from other oil seeds (Onsaard, 2012; Yüzer & Gençcelep, 2023).

Given the high protein content of dehulled sesame meal, researchers have explored various extraction techniques to maximize its yield and functionality. For example, ohmic heating (OH) is a promising alternative technology for the extraction of intracellular compounds that can promote rapid and homogeneous extraction with high-energy efficiency. By applying, a moderate electric field through a semi-conducting material that resists the passage of electric current, heat is generated directly inside the volume of the material and causes the rearrangement of the cell membrane, resulting in the creation of pores (electrical permeability). The pores cause the release of intracellular components (Ferreira-Santos et al., 2019; Rodrigues et al., 2019). In addition, this "green" technology may help to reduce the environmental impact of extraction processes, water/solvent consumption, waste generation due to higher extraction efficiency, energy consumption, processing time (Chemat et al., 2017; Rocha et al., 2018). Ohmic heating has a wide range of different applications in the food industry including drying food, enzyme removal, fermentation, extraction, heating, decolorization, and thawing (Keshani et al., 2020, 2022; Keshani et al, 2024; Sarkis et al., 2013). This study aimed to optimize functional properties of foaming capacity and stability of sesame protein from dehulled sesame meal using the response surface methodology (RSM) to develop a new protein source from oilseed waste.

Materials and methods

First, the milled sesame byproduct and the resulting flour was sieved using a 30-mesh sieve and became free of any foreign material. The resulting flour was defatted by hexane solvent. To remove the remaining solvent, the degreased samples were dried at ambient temperature under the hood.

The extraction of protein from the samples was performed according to the RSM

Table *2*, which included 3 independent variables: pH, ammonium sulfate concentration, and voltage. Initially, ammonium sulfate solutions with different concentrations of 0.1%, 0.2%, and 0.3% by weight/volume were prepared. A ratio of 1:10 of sesame flour powder to ammonium sulfate solution was utilized in each ohmic cell test. The thermocouple was connected, and the voltage was applied along with a frequency of 50 Hz until the center of the sample reached a temperature of 30 degrees of Celsius. To ensure the preservation of native sesame protein structure, the extraction temperature was carefully selected. A mild temperature of 30 °C was used to minimize heat-induced denaturation, allowing observed changes in functional properties (foaming capacity and stability) to result mainly from pH, ammonium sulfate concentration, and applied voltage rather than thermal effects. Maintaining extraction temperatures below 40 °C has been recommended for plant proteins to preserve their structure and functionality(Tang et al., 2006). Subsequently, the sample was removed from the cell, and the dependent parameters were immediately measured in three repetitions.

Foaming capacity (FC) and foam stability (FS)

To measure the foam-forming power, 250 mg of protein was mixed with 25 ml of distilled water, and the pH of the samples was adjusted to 7. The protein mixture was then mixed in a mixer for 1 minute. Subsequently the volumes caused by the formation of foam at the initial moment of formation and after 60 minutes were measured using the following equations (Barzani & Zamindar, 2025; Deng et al., 2011).

eq 1

$$\text{Foam capacity}(\%) = \frac{(\text{volume of foam after whipping} - \text{volume of foam before whipping})\,ml}{(\text{volume of foam before whipping})\,ml} \times 100$$

eq 2

$$\text{Foam stability}(\%) = \frac{(\text{Volume of foam after 60 minutes} - \text{volume of foam before whipping})\,ml}{(\text{volume of foam before whipping})\,ml} \times 100$$

Protein yield extracted from sesame meal

The yield value of the method was calculated based on eq (Salgado, Molina Ortiz et al. 2011).

eq 3

$$\text{Protein Yield}(\%) = \frac{\text{Weight (g) of extracted protein powder}}{\text{Weight (g) of defatted sesame meal}} \times 100$$

Statistical investigation of optimization of process conditions by response surface method

To model and optimize the conditions of protein extraction from sesame byproduct, the influence of independent variables including pH, ammonium sulfate solution concentration, and voltage, the response surface method (RSM), and Design Expert software were used. For this purpose, the central composite design and 6 replications at the central point were used through 32 runs to investigate the functional properties of sesame byproducts. The protein extraction efficiency of the peeled sesame meal was compared with the prediction of the model by the T-student test at the probability level of 0.05.

Table 1 shows the real and coded values of independent variables used for the experimental design of protein extraction of peeled sesame meal.

Table 1.The real and coded values of independent variables for experimental design

Factor	Name	Minimum	Maximum	Coded Low	Coded High	Mean	Std. Dev.
A	Ammonium sulfate concentration (g/Lit)	0.1	0.3	-1 ↔ 0.10	+1 ↔ 0.30	0.2000	0.0803
B	Voltage (v)	25	35.00	-1 ↔ 9.00	+1 ↔ 11.00	10.00	0.8032
C	pH	9	11	-1 ↔ 25.00	+1 ↔ 35.00	30.00	4.02

Table 2. Experimental design of independent variables proposed by Design Expert

Run	A: Solution concentration (g/Lit)	B: pH	C: Voltage(V)	Foaming capacity(ml)	Foam stability 1 (ml/60min)	Run	A: Solution concentration (g/Lit)	B: pH	C: Voltage(V)	Foaming capacity(ml)	Foam stability 1 (ml/60min)
1	0.2	9	30	2.7	97.86	17	0.3	9	25	3	99.03
2	0.3	10	30	3	99	18	0.2	10	30	4.5	97.61
3	0.3	9	25	3.6	99	19	0.2	10	30	2.81	97.94
4	0.2	9	30	4	98	20	0.2	11	30	4.44	96.81
5	0.1	9	35	9.42	95.9	21	0.1	9	25	3.55	98.59
6	0.2	11	30	3.33	97.8	22	0.2	10	30	3.5	98.07
7	0.1	10	30	3.16	98.6	23	0.1	11	25	3	98.44
8	0.1	11	25	3	98.5	24	0.2	10	35	4	97.29
9	0.3	9	35	2.09	98.6	25	0.1	11	35	4.5	97.61
10	0.3	11	35	3	99	26	0.2	10	30	3.1	97.14
11	0.3	11	35	2.5	98.5	27	0.3	10	30	2.5	99.02
12	0.1	9	35	8.5	95.8	28	0.1	9	25	3.34	98.81
13	0.3	11	25	12.05	94.7	29	0.3	9	35	1.32	99.29
14	0.2	10	25	4.2	97.3	30	0.2	10	25	4	97.35
15	0.1	11	35	3	98.3	31	0.1	10	30	2	99.01
16	0.3	11	25	12.77	95	32	0.2	10	35	2.5	97.07

Results and discussion

Foaming capacity

Foam is a dispersion of a high volume of gas within a liquid matrix and is utilized in various applications such as malt beverages, bread, confectionery creams, ice cream, and marshmallows (Indrawati et al., 2008). Foam characteristics are usually evaluated according to the two indicators of initial volume (foaming capacity) and remaining volume over time (foam stability) Foam stability refers to the ability of the foam to maintain its volume, bubble size, and liquid content over a certain period(Naji et al., 2013).

According to the results of the analysis of variance (while the Lack of Fit was not significant ($F = 2.34$, $p = 0.086$), confirming the suitability of the model. The model showed good agreement with the experimental data ($R^2 = 0.9440$, Adj $R^2 = 0.9210$, Pred $R^2 = 0.8820$). The Adequate Precision value (24.82) also indicated a strong signal-to-noise ratio.

According to the analysis of the variance, the suitable model for predicting the effect of ammonium sulfate concentration, voltage, and pH variables on the foaming capacity of sesame flour protein was the quadratic model according to the equation (1). The results indicated that pH and voltage significantly influenced the foaming capacity ($p \leq 0.05$), whereas ammonium sulfate concentration alone was not significant ($p > 0.05$). However, the interaction effects between pH and ammonium sulfate, pH and voltage, and ammonium sulfate and voltage were all significant ($p < 0.01$).

$$Y= (+2.95) + (0.1180\ A) + (0.5035\ B) - (0.5840C) + (1.98AB) - (2.19\ AC) - (1.60\ BC) - (0.0211\ A^2) + (0.9314\ B^2) + (0.9889\ C^2) \quad \text{Eq .1}$$

In this relation, Y is the Foaming capacity of dehulled sesame meal protein (ml), A stands for solution concentration (g/Lit), B for pH and C is the symbol for voltage (V).

Table 3) to evaluate the response parameter of foaming capacity, the F-value of the quadratic model was equal to 41.17. The interaction terms were highly significant ($p < 0.0001$), while the Lack of Fit was not significant ($F = 2.34$, $p = 0.086$), confirming the suitability of the model. while the Lack of Fit was not significant ($F = 2.34$, $p = 0.086$), confirming the suitability of the model. The model showed good agreement with the experimental data ($R^2 = 0.9440$, Adj $R^2 = 0.9210$, Pred $R^2 = 0.8820$). The Adequate Precision value (24.82) also indicated a strong signal-to-noise ratio.

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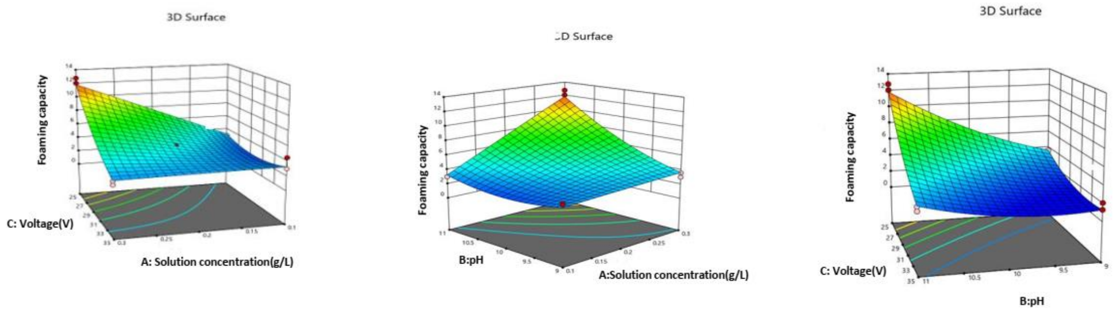
In this relation, Y is the Foaming capacity of dehulled sesame meal protein (ml), A stands for solution concentration (g/Lit), B for pH and C is the symbol for voltage (V).

Table 3. Variance analysis of the effect of independent variables on the foam formation capacity of Sesame waste protein at zero moment

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	212.56	9	23.62	41.17	< 0.0001	significant
A- Solution concentration	0.2785	1	0.2785	0.4855	0.4932	
B- pH	5.07	1	5.07	8.84	0.0070	
C-Voltage	6.82	1	6.82	11.89	0.0023	
AB	62.49	1	62.49	108.94	< 0.0001	
AC	76.74	1	76.74	133.78	< 0.0001	
BC	41.15	1	41.15	71.74	< 0.0001	
A^2	0.0024	1	0.0024	0.0041	0.9495	
B^2	4.57	1	4.57	7.97	0.0099	
C^2	5.16	1	5.16	8.99	0.0066	
Residual	12.62	22	0.5736			
Lack of Fit	5.15	5	1.03	2.34	0.0860	not significant
Pure Error	7.47	17	0.4393			
Cor Total	225.18	31				
Std. Dev.	0.7574		R^2	0.9440		
Mean	4.14		Adjusted R^2	0.9210		
C.V. %	18.31		Predicted R^2	0.8820		
			Adeq Precision	24.8177		



(a) (b) (c)

Figure 1. Three-dimensional diagram of the interaction effect of ammonium sulfate concentration and voltage (a), (b), pH and ammonium sulfate concentration, pH and voltage (c), on the foaming capacity of sesame flour protein at the moment of foam formation

As Figure 1 shows, increasing the voltage reduced the foaming capacity of dehulled sesame meal protein. In contrast, an increase in alkaline pH and ammonium sulfate concentration from 0.1% to 0.3%, enhanced foaming capacity. The maximum foaming capacity was observed under conditions of high pH, high ammonium sulfate concentration, and low voltage.

The improvements in foaming capacity (FC) and foaming stability (FS) observed in this study can be attributed to enhanced protein solubility, partial unfolding, and the formation of more stable interfacial films. These structural changes promote adsorption of protein at the air–water interface, thereby supporting foam development. Our findings are consistent with previous studies on plant proteins (de Souza et al., 2020; Yang et al., 2021), which identified structural flexibility and interfacial activity as key determinants of foaming properties.

Comparison with ultrasonic-assisted extraction indicates important differences. Martínez-Velasco et al. (2018) and Karabulut & Yemiş (2022) reported that ultrasound treatment improved foaming capacity by ~40% and stability by 6.7% compared to conventional alkaline extraction. These effects were linked to partial denaturation, exposure of hydrophobic groups, and reduction in particle size, which facilitated smaller and more stable air bubbles. In contrast, our results show that while ohmic-assisted extraction under alkaline pH enhanced foaming capacity, excessive voltage reduced it, likely due to over-denaturation or aggregation caused by strong electric fields (Karabulut & Yemiş, 2022; Martínez-Velasco et al., 2018; Yildiz et al., 2025). Therefore, both ohmic and ultrasonic methods can improve foaming through structural modifications, but their mechanisms and optimal conditions differ.

Foaming stability

Foaming stability (FS) is another important functional property of proteins, which indicates the amount of foam after a predetermined time relative to its initial volume. As shown in According to the analysis of the variance, the quadratic model was suitable for predicting the effect of ammonium sulfate concentration, voltage, and pH variables on the stability of sesame protein foam after 60 minutes (Eq. 2). The effects of model, pH, the interactions of pH and ammonium sulfate concentration, pH and voltage, and the interaction of ammonium sulfate concentration and voltage were significant on the stability of sesame protein foam after 60 minutes ($p<0.01$).

$$Y = (+97.85) + (0.0875A) - (0.3001B) + (0.0272C) - (0.7751AB) + (0.9075AC) + (0.7920\,BC) + (0.9787A^2) - (0.3065\,B^2) - (0.6827C^2) \quad \text{Eq .2}$$

In this relation, Y is the Foaming stability of dehulled sesame meal protein (ml), A stands for solution concentration (g/Lit), B for pH and C is the symbol for voltage (V).

Table *4*, the analysis of variance results for evaluating the response parameter of foam stability revealed that the F value of the quadratic model was equal to 35.36 indicating the significance of the model. The p-value of interactions was less than 0.0001, so it had a significant effect on the model. The F value for the lack of fit in this model was equal to 1.77 which was not significant, showing that the model fitted well with the experimental data. The R-squared value of 0.9353 quite close to one indicated the high consistency of the model with the experimental data. The Adequate Precision of 20.0656 indicates a sufficient signal. The values of Pre R-Squared and Adjusted R-Squared were 0.8588 and 0.9089, respectively.

According to the analysis of the variance, the quadratic model was suitable for predicting the effect of ammonium sulfate concentration, voltage, and pH variables on the stability of sesame protein foam after 60 minutes (Eq. 2). The effects of model, pH, the interactions of pH and ammonium sulfate concentration, pH and voltage, and the interaction of ammonium sulfate concentration and voltage were significant on the stability of sesame protein foam after 60 minutes ($p<0.01$).

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In this relation, Y is the Foaming stability of dehulled sesame meal protein (ml), A stands for solution concentration (g/Lit), B for pH and C is the symbol for voltage (V).

Table 4. Variance analysis of the effect of independent variables on the stability of Sesame waste protein foam 60 minutes after foam formation protein

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	40.86	9	4.54	35.36	< 0.0001	significant
A- Solution concentration	0.1533	1	0.1533	1.19	0.2864	
B- pH	1.80	1	1.80	14.03	0.0011	
C-Voltage	0.0148	1	0.0148	0.1149	0.7378	
AB	9.61	1	9.61	74.85	< 0.0001	
AC	13.18	1	13.18	102.60	< 0.0001	
BC	10.03	1	10.03	78.14	< 0.0001	
A^2	5.05	1	5.05	39.33	< 0.0001	
B^2	0.4953	1	0.4953	3.86	0.0623	
C^2	2.46	1	2.46	19.14	0.0002	
Residual	2.83	22	0.1284			
Lack of Fit	0.9658	5	0.1932	1.77	0.1737	not significant
Pure Error	1.86	17	0.1094			
Cor Total	43.69	31				
Std. Dev.	0.3584		R^2	0.9353		
Mean	97.84		Adjusted R^2	0.9089		
C.V. %	0.3663		Predicted R^2	0.8588		
			Adeq Precision	20.0656		

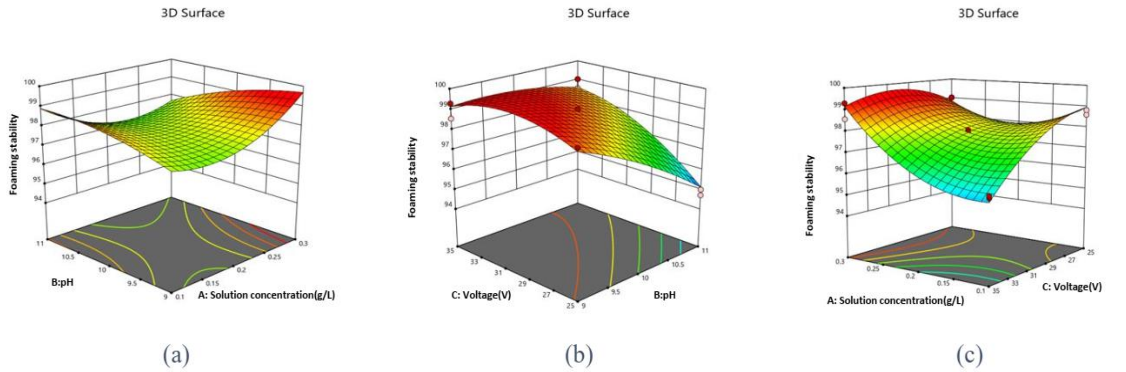

Figure 2. Three-dimensional diagram of the interaction effect of ammonium sulfate concentration and voltage (a), (b), pH and ammonium sulfate concentration, pH and voltage (c), on the foam stability of sesame flour protein after 60 minutes.

According to Figure 2, it is clear that with the increase in voltage and concentration of ammonium sulfate, the stability of the foam of sesame flour protein increased, while with the increase in alkaline pH, the stability of foam has decreased.

Our findings demonstrated that the foaming stability (FS) of sesame protein is strongly influenced by pH, ionic strength (ammonium sulfate concentration), and applied voltage, with synergistic effects observed between ammonium sulfate and voltage. Highly alkaline conditions (pH >10.5) significantly reduced FS, even at higher voltage or salt concentrations, likely due to excessive ionization of protein side chains weakening intermolecular interactions and decreasing the strength of the interfacial film.

Proteins act as effective foaming agents because they can rapidly adsorb at the air–water interface and partially unfold to form a strong and flexible interfacial film, maintaining foam cohesion(Zhang et al., 2011).Foaming properties depend on adsorption to the air–water boundary, conformational change and structural reorganization, and formation of cohesive viscoelastic films via intermolecular interactions(Amagliani et al., 2017). The observed improvement in FS with increased voltage and ammonium sulfate concentration may be explained by enhanced protein solubility and controlled unfolding under an electric field, which strengthens the interfacial films.

These results align with previous studies showing that protein foaming properties are strongly dependent on solubility, structural flexibility, and the formation of cohesive interfacial films (Lam et al., 2018; Taha et al., 2022; Zhang et al., 2017). Similar improvements in foaming capacity and stability have been achieved through protein modification methods such as microwave, ultrasound, high-pressure homogenization (HHP), Maillard conjugation, and enzymatic hydrolysis, where partial unfolding or reduced aggregate size enhanced interfacial adsorption and film elasticity(Baskıncı & Gul, 2023; Jambrak et al., 2009; Khan et al., 2011; Naseri et al., 2020; Sengar et al., 2022; Wang et al., 2024; Zhang et al., 2020). However, some methods, such as excessive sonication or microwave-assisted extraction, may lead to protein aggregation or lower foam stability compared to alkaline or ohmic-assisted treatments (Ochoa-Rivas et al., 2017; Shokri et al., 2022). Compared with these approaches, ohmic treatment offers unique advantages as a clean, energy-efficient, and scalable method that simultaneously promotes solubility and controlled unfolding, resulting in more stable foams without excessive protein damage. From an industrial perspective, these findings highlight the potential of sesame protein as a plant-based foaming agent for aerated food systems such as cakes, whipped toppings, ice creams, beverages, and egg-free mayonnaise (Achouri et al., 2012; Hu et al., 2023; Karshenas et al., 2018).

Optimization of Response Parameter

To optimize the foaming capacity and foam stability of the protein extracted from dehulled sesame meal, the independent variables were set within the defined ranges, and the dependent variables were assumed maximum. Table 5 presents the optimal extraction conditions suggested by the Design-Expert software, along with the experimental results obtained in triplicate. According to Table 5and the results of the student's t-test, no significant difference was observed between the experimental values and the predicted values suggested by the software, confirming the validity and accuracy of the developed model. The yield of protein at optimal conditions were determined 68.78±1.2 (%).

Table 5. Recommended conditions of the software for optimizing the process and the tests performed

	Solution concentration(g/L)	pH	Voltage (V)	Foaming capacity	Foam stability (60 min)
Predicted conditions	0.3	10	25	6.905	97.253
Experiments performed	0.3	10	25	6.97± 0.292^{ns}	97.32± 0.276 ^{ns}

ns: not significant (p ≥0.05)

Conclusion

In this research, the optimization and evaluation of the functional characteristics of sesame flour were performed using an ohmic device and response surface methodology (RSM). Parameters including pH, ammonium sulfate concentration, and voltage were selected as independent variables. The results showed that the quadratic model could accurately predict the responses, and the predicted values were in strong agreement with the experimental data. Analysis of the independent variables showed that pH and voltage had a significant effect on foaming capacity, whereas ammonium sulfate concentration was not statistically significant. In the case of foam stability, pH and its interactions with the other variables played a significant role. In general, the highest foaming capacity was obtained at alkaline pH levels, low voltage, and high salt concentration, while foam stability improved under high voltage and salt concentration conditions and lower pH. This contrast in response to pH between the two functional parameters highlights the need to carefully design the extraction process to achieve simultaneous optimization. The final optimal protein extraction conditions included pH of 10, ammonium sulfate concentration of 0.3%, and voltage of 25 V. A t-test comparison between the predicted values and the experimental results showed no significant difference (p > 0.05), confirming the model's reliability. Overall, the results demonstrated that sesame protein extracted using ohmic heating had favorable functional properties, particularly in terms of foaming capacity and stability. These qualities make it a promising candidate for use in foamed food products such as desserts, plant-based creams, processed breads, and other innovative formulations. *Furthermore*, the use of ohmic extraction, along with advanced statistical approaches, provides an efficient and sustainable method for enhancing the added value of biomaterials and agricultural wastes.

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