Tribhuvan University Journal of Food Science and Technology
2 (2023) 26-31
DOI: https://doi.org/10.3126/tujfst.v2i2.66458

ORIGINAL RESEARCH PAPER

Effects of Pressure and Press Time on the Physical Quality of Dried-Frozen Tofu

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Abstract

This study aimed to produce tofu from locally sourced white soybeans (Glycine max L. Merr.) by employing varying pressure and press time parameters, ranging from 1 to 5 kg/cm² and 8 to 90 min, respectively. Employing a robust experimental design (Central composite design, face centered, 2-factor, 3-level, with 13 runs), facilitated through Design-Expert® v 10.0.1, a design of experiment (DOE) tool, enabled a systematic exploration of the processing space. Following production, the fresh tofu batches underwent a freezing stage at -20°C for 7 days, subsequent thawing in water (at 50°C for 30 min), and final drying in an electric oven at 75°C until reaching a moisture content of 10%. Response surfaces were meticulously generated to comprehensively understand the intricate interplay between pressure, press time, and key responses, such as rehydration ratio, pore size, and bulk density. A thorough data analysis, utilizing Design Expert® v 10.1.1 for pore size and rehydration ratio, and Genstat® v 12.0.1 for textural attributes, revealed statistically significant (p≤0.05) impacts of processing variables on the sensory attributes of tofu. Leveraging desirability constraints aimed at minimizing pressure, press time, and pore size while maximizing rehydration ratio, the optimized conditions were determined as 3.91 - 4.16 kg/cm² for pressure and 8.0 min for press time. Under these optimal conditions, the resulting dried-frozen tofu exhibited a maximum rehydration ratio of 0.275 mm and an average internal pore size of 1.335. These findings not only contribute valuable insights into the tofu production process but also offer a practical guide for enhancing the quality of dried-frozen tofu while minimizing resource inputs. This optimized approach holds promise for efficient and sustainable large-scale tofu manufacturing.

Keywords:
Dried-frozen tofu
Rehydration ratio
Soymilk
Coagulant
Press time

Article history:
Received: 16 Nov 2023
Received in revised form: 25 Jan 2024
Accepted: 01 Mar 2024
Available online:

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Introduction

Tofu, derived from the water-soluble proteins of soybeans, stands as a versatile and widely used ingredient in traditional cuisines worldwide (Jhonson, 1984). Its neutral flavor, ease of preparation, and adaptability in various dishes contribute to its popularity. However, the inherent perishability of fresh tofu, with a high moisture content (up to 90%) and a pH range of 6-7, creates a conducive environment for microbial spoilage, limiting its shelf-life to a mere 2-3 days even under refrigeration (Ali, 2010; Shin et al., 2010). The implementation of modern processing and preservation techniques is essential to extend this shelf-life (Ali et al., 2021).

Despite its seemingly simple production process involving the preparation of soymilk and subsequent coagulation to form bean curd, achieving consistent high-quality tofu is a complex endeavor (deMan et al., 1986; Chang, 2006). This complexity has fueled ongoing research efforts in the field, as highlighted by various authors, including Shurtleff & Aoyagi (1979), Wang et al. (2020) and Zheng et al. (2020).

Variations of regular tofu, such as 'frozen tofu' and 'dried-frozen tofu,' involve the crystallization and removal of water, resulting in distinctive textures and extended shelf stability (Keshun, 1999; Shurtleff & Aoyagi, 2013). Dried-frozen tofu, in particular, boasts an average shelf life of 8 months and offers versatility as a protein ingredient for diverse culinary applications (Watanabe & Kishi, 1984).

The quality of dried-frozen tofu is intricately linked to numerous processing and raw material factors, including the water-to-soybean ratio, soybean soaking conditions, grinding processes, heat treatment, coagulant type, and concentration, and pressing parameters (deMan et al., 1986; Keshun, 1999). While pressure and press time have been extensively studied in the context of fresh tofu, limited literature exists on their effects specifically on dried-frozen tofu (Chang, 2006; Shurtleff & Aoyagi, 2013).

Understanding the relationships between pressure, press time, and pore size is critical for optimizing the production of dried-frozen tofu. Shurtleff & Aoyagi (2013) suggest that increased pressure and press time for dried-frozen tofu contribute to water removal, resulting in a firmer curd with finer grain structure and delicate texture. However, the existing body of literature on the relationships between pressure, press time, and pore size in dried-frozen tofu remains sparse.

This study aims to bridge this gap by systematically exploring the effects of pressure and press time on the physicochemical properties of dried-frozen tofu, with a focus on pore size and rehydration capacity. The findings promise to contribute valuable insights to the field of tofu research, offering practical guidance for optimizing the production of dried-frozen tofu with enhanced quality and versatility.

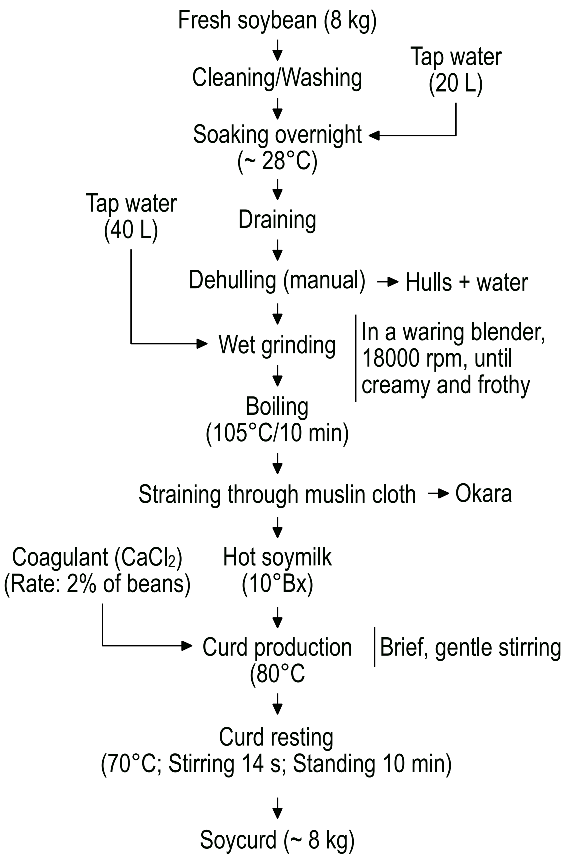

Figure 1
Preparation of soy curd for tofu making

Materials and Methods

Collection of soybeans

Soybean (local, white variety) was bought from a local market (Krishi bazar) in Dharan, Nepal. Interviews with the traders revealed that the beans were produced in the Terhathum district (Basantapur).

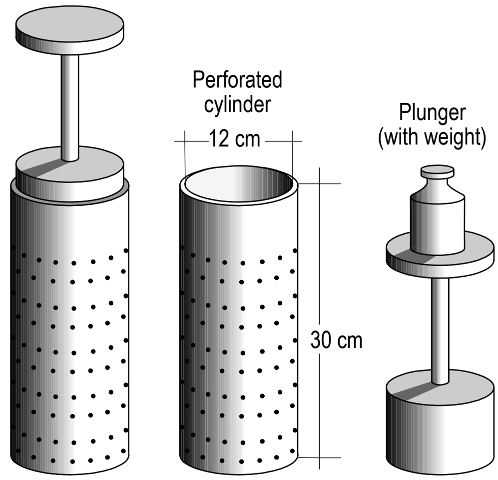

Figure 2
Locally fabricated steel tofu press

Design of experiment (DOE)

The curd was portioned into 13 lots according to the Central Composite (face-centered, 2-factor, 3-level) design of the experiment (DOE) generated using Design-Expert® v. 10.0.1 (a DOE program). The pressure (1-5 kg/cm^2) and press time (8-90 min) combination used in this study are given in Table 1. The responses were rehydration ratio and pore size (mm). The lots were pressed in locally fabricated perforated steel cylinders (~3.5 L capacity) having snugly fitting plungers (Figure 2). The workflow for dried-frozen tofu preparation and analysis following curd preparation is given in Figure 3.

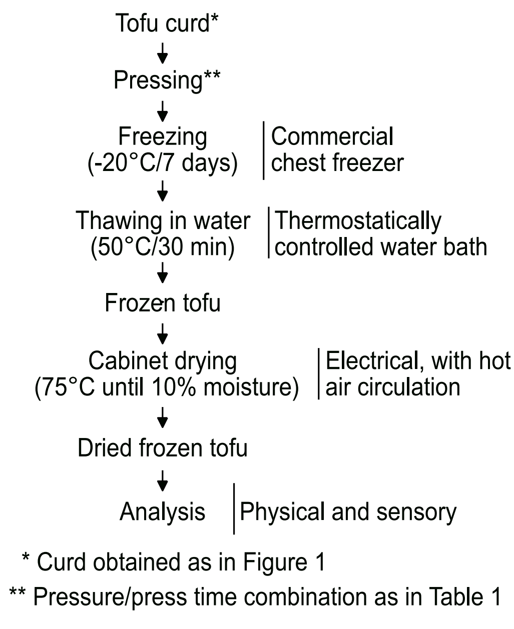

Figure 3
Workflow for dried-frozen tofu making

Table 1
Experimental plan for pressure/press time combination and physical response variables

Run	Factor 1	Factor 2
	A: Pressure (kg/cm^2)	B: Time (min)
1	1	49
2	3	49
3	3	90
4	3	49
5	3	49
6	3	49
7	3	49
8	1	90
9	5	90
10	5	49
11	5	8
12	3	8
13	1	8

Thawing and drying of tofu

As depicted in Figure 3, the frozen tofu was thawed in warm water (50°C) to melt the ice crystals, cut into small cubes (3×3×3 cm^3) and then dried in an electric oven (cabinet dryer) at a controlled temperature of 75°C to a final moisture content of 10%. Rather than periodically checking the moisture content of tofu while being dried, the following formula that relies on only periodic weighing of tofu cubes undergoing drying was used to predict the end of drying:

$$X = w_i \times \frac{100 - x}{100 - y}$$

Where X = mass of sample after reaching the desired moisture level (y); w_i = mass of sample taken for drying; x and y are initial and final (desired) % moisture content of the sample.

Physicochemical parameters

The moisture content of the initial sample was determined using a hot air oven, with 10 g of tofu being dried at 130°C until constant weight (Egan et al., 1981).

Rehydration ratio was determined as per Ranganna (1986). Approximately 100 g of dried tofu was dipped in 400 ml of distilled water at 50°C for 30 min. After rehydration, the sample was removed from distilled water, surface moisture was absorbed carefully with tissue paper, and then weighed. The rehydration ratio was calculated as:

$$\text{Rehydration ratio} = w_r / w_d$$

Where w_r = weight of tofu after rehydration, w_d = weight of dry tofu (before rehydration).

Measurement of density of frozen tofu done indirectly by immersing the weighed tofu block in water and measuring the volume of water displaced.

Pore size was evaluated on the thawed tofu samples by cutting them into very thin slices (~0.25 mm) with a sharp razor blade. Micrometric measurements were taken in a calibrated microscope under 100× magnification.

Textural properties of rehydrated tofu at room temperature can be computed by using Texture Analyzer Stable Micro Systems (Jain & Mhatre, 2009), but due to the lack of such an instrument, analysis was done by the sensory method.

In this sensory analysis, the panelists were first briefed on how to score the sensory attributes, viz., (i) Hardness as the force necessary to attain a given deformation of the material - tofu with greater hardness means harder and firmer; (ii) Cohesiveness as work required to overcome the internal bonding of the material - tofu with greater cohesiveness requires more work to break down the internal bonding; (iii) Springiness as the rate at which a deformed material recovers to its undeformed condition after the deforming force is removed - tofu with higher springiness possesses higher elasticity; and (iv) Chewiness as the energy required for masticating a solid food product to a state of readiness for swallowing and is instrumentally quantified as a product of hardness × cohesiveness × springiness - tofu with greater chewiness is stiffer and harder to eat (Szczesniak, 1963). A modification of 5-point hedonic test (1 = least, 2 = less, 3 = medium, 4 more, and 5 = most) as given in Ranganna (1986) was adopted for the analysis, employing 10 semi-trained panelists.

Data analysis

Optimization of process variables

To minimize the expensive resources (energy and time), it is highly desirable that the least possible pressure and press time be used, without compromising the quality of the product. With this in view, the following criteria (Table 2) were set for optimizing through Design-Expert® v10.0.1 (a DOE program).

Table 2
Optimization criteria for use in Design Expert® v10.0.1

Criteria	Goal	Weight	Importance
A: Pressure (kg/cm^2)	Minimize	1	+ + + + +
B: Time (min)	Minimize	1	+ + + + +
Rehydration ratio	Maximize	1	+ + + + +
Pore size (mm)	Minimize	1	+ +

The goal behind placing the greatest emphasis (5 '+' signs, Table 2) on minimizing process conditions, viz., pressure and press time, was to minimize resources (pressure, energy, and time). An attempt was made to maximize the response rehydration ratio (with emphasis) to ensure that the rehydrated product resembled, as close as possible, the original product. Minimization of pore size was thought necessary for faster rehydration, the explanation behind which has been given by Harnkarnsujarit et al. (2016). Hence an optimal solution was attempted using the optimization function of Design Expert® v10.0.1.

During optimization, the DOE software's default criterion 'Desirability' is always set to maximum. In certain cases, however, the maximum desirability value is not necessarily the sole determinant for optimization (Myers et al., 2009). This means that one must be careful in choosing from the generated optimal solutions.

Since the textural study (hardness, cohesiveness, springiness, and chewiness) of the frozen tofu entailed sensory approach, the data were also subjected to 2-way ANOVA using the statistical tool Genstat® v12.0.1. Out of the 13 runs obtained from Design Expert®, only the 9 runs having unique pressure-press time combinations (pairs) were used to avoid an unbalanced design: Response data of replicate combinations were averaged to give a single mean value. Post-hoc test was carried out employing Fisher's LSD (least significant difference) at 5% level of significance.

Results and Discussion

Analysis of textural properties

A summary of ANOVA and post-hoc test of data on textural properties (hardness, cohesiveness, springiness, and chewiness) is given in Table 3.

Based on Table 3, the superiority (in descending order) of the textural attributes of frozen tofu can be rewritten as:

Hardness: [D] > [A/G] > [B/H] > [C/I]

Cohesiveness: [D] > [A/E/G] > [B/F/H] > [C/F/H]

Springiness: [D] > [A] > [B/E/G] > [B/G/H] > [C/F] > [I]

Chewiness: [D/A] > [E/G] > [B/G] > [B/H] > [C/F/H] > [I/F]

The result shows that treatment D, with the highest pressure (5 kg/cm^2) and longest press time (90 min), consistently secured the highest score for all the attributes. This agrees with the statements in Szczesniak et al. (1963) and Szczesniak & Bourne (1995). Treatment A (the lowest pressure and press time) secured the second ranking, which contrasts with expectation and also defies a simple explanation.

Pore size of frozen tofu

The present study shows how pressure and press time affects the pore size of the frozen tofu. Contrary to the logical expectation that higher pressure and longer press time should produce tofu of smaller pore sizes, this finding shows that smaller pore sizes can be obtained by using lesser pressure for a longer time. The result, therefore, warrants further study. Harnkarnsujarit et al. (2016) have discussed the relationship between the microstructure of tofu with freezing temperature and rehydration (smaller void space embedded in the dehydrated matrices resulted in a faster water uptake rate), but the influence of pressure and press time on the pore size of dried-frozen tofu has not been studied.

Table 3
Summary of ANOVA for textural attributes of frozen tofu

Sample	*Textural attribute (mean score)*			
	Hardness	***Cohesiveness***	***Springiness***	***Chewiness***
A (1, 8)	$3.46^{d} \pm 0.52$	$3.73^{d} \pm 0.47$	$3.73^{e} \pm 0.47$	$3.82^{f} \pm 0.40$
B (5, 8)	$2.64^{b} \pm 0.50$	$2.91^{c} \pm 0.30$	$2.82^{cd} \pm 0.40$	$2.82^{cd} \pm 0.40$
C (1, 90)	$2.18^{a} \pm 0.40$	$2.36^{b} \pm 0.50$	$2.36^{b} \pm 0.50$	$2.36^{b} \pm 0.50$
D (5, 90)	$4.18^{e} \pm 0.40$	$4.18^{e} \pm 0.40$	$4.09^{f} \pm 0.54$	$4.18^{f} \pm 0.40$
E (1, 49)	$3.09^{c} \pm 0.30$	$3.36^{d} \pm 0.50$	$3.09^{d} \pm 0.30$	$3.27^{e} \pm 0.47$
F (5, 49)	$2.09^{a} \pm 0.30$	$2.73^{bc} \pm 0.47$	$2.27^{b} \pm 0.47$	$2.09^{ab} \pm 0.30$
G (3, 8)	$3.18^{cd} \pm 0.40$	$3.54^{d} \pm 0.52$	$3.00^{cd} \pm 0$	$3.18^{de} \pm 0.40$
H (3, 90)	$2.73^{b} \pm 0.47$	$2.73^{bc} \pm 0.47$	$2.73^{c} \pm 0.47$	$2.46^{bc} \pm 0.52$
I (3, 49)	$2.00^{a} \pm 0$	$1.91^{a} \pm 0.30$	$1.91^{a} \pm 0.30$	$1.82^{a} \pm 0.40$
LSD	0.33	0.38	0.35	0.38

Note. At 5% level of significance; the pair of figures in the parenthesis alongside the treatments A, B, C, etc., indicate pressures (in kg/cm^2) and press time (in min), respectively; Values in the column bearing the superscript letter(s) are not significantly different at 5% level of significance; Values following '±' are standard deviations of scores given by 10 panelists for the corresponding attribute and treatment.

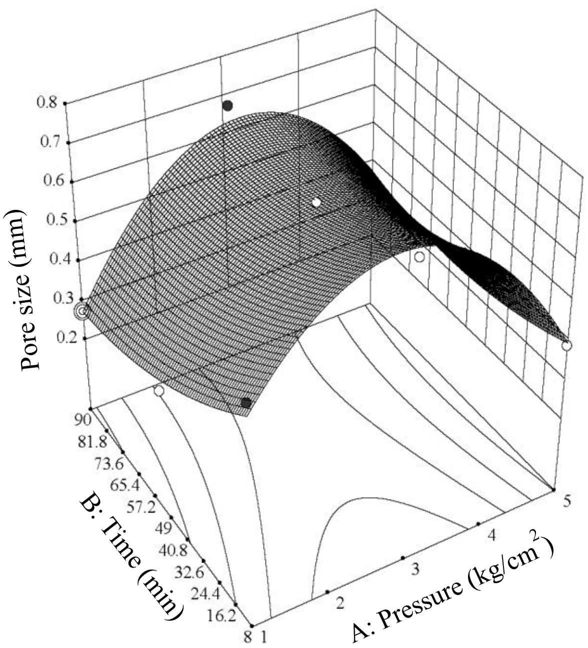

Figure 4
Model response surface graph for pore size

The response surface (Figure 4) shows that frozen tofu with pore size averaging 0.275 mm can be prepared by pressing it at 1 kg/cm^2 for 90 min. Since the press time is too long, optimization was done with Design Expert® v10.0.1 to reduce the time without significantly affecting the pore size. The optimization result is given in section without significantly affecting the pore size.

The 'Fit summary' and 'Model summary statistics' obtained from Design Expert v10.0.1 suggest a quadratic model. The ANOVA of response (pore size) to the Response Surface Quadratic Model showed that the model is significant. Consequently, the final equation (1) (generated by the DOE tool) in terms of actual factors is:

$$\text{Pore size} = +\,0.25 + 0.42 \times \text{Pressure} - 7.00 \times 10^{-3} \times \text{Time} + 7.48 \times 10^{-4} \times \text{Pressure} \times \text{Time} - 0.08 \times \text{Pressure}^2 + 3.08 \times 10^{-5} \times \text{Time}^2 \quad (1)$$

Rehydration ratio

The 'Model summary statistics' generated in‖ Design Expert 10.0.1 suggest quadratic model. The ANOVA of response (rehydration ratio) to Response Surface Quadratic Model shows that the model is significant, i.e., A, A^2 and B^2 are significant where A is the pressure and B is the press time. Consequently, the final equation (2) (generated by the DOE tool) in terms of actual factors is:

$$\begin{aligned} \text{Rehydration Ratio} = &+ 1.43 \\ &- 0.16 \times \text{Pressure} \\ &- 1.38 \times 10^{-3} \times \text{Time} \\ &- 4.72 \times 10^{-4} \times \text{Pressure} \times \text{Time} \\ &+ 0.03 \times \text{Pressure}^2 \\ &+ 2.02 \times 10^{-5} \times \text{Time}^2 \quad (2) \end{aligned}$$

The model response graph for rehydration ratio is shown in Figure 5. Rehydration is a major desired property of freeze-dried foods. Water imbibition into freeze-dried materials takes place by capillary flow driven by capillary pressure gradients rather than by diffusion. Smaller pore sizes in the dehydrated matrices result in a faster water uptake (Harnkarnsujarit et al., 2016).

The response surface curve (Figure 5) shows a maximum rehydration ratio of 1.335 that can be achieved by pressing tofu for 8 min at a pressure of 5 kg/cm^2, implying that maximum pressure for the shortest duration would be desirable for improving the rehydration ratio. However, this value is almost twice less than the value reported by Harnkarnsujarit et al. (2016), which could be due to pore size differences between the studies (0.275 mm in this study against 0.015-0.12 mm in the said authors' work).

Process optimization

Using the optimization criteria given in Table 2 (minimum pressure and press time) in DOE tool, 5 possible solutions could be generated (Table 4).

As can be seen from Table 4, solution 1 gives the maximum desirability (0.68) based on the criteria set for the process variables and responses. However, the maximum value of desirability is not necessarily the sole determinant for optimization (Myers et al., 2009). In the present case, press time outweighs the importance of the pressure applied because less press time means increased productivity. It therefore implies that any of the remaining four solutions (Table 4, solutions 2, 3, 4 and 5) can be selected as the best solution: the press time can be reduced by more than double (8 min against ~21 min) without significantly affecting the physicochemical properties of frozen tofu and dried-frozen tofu.

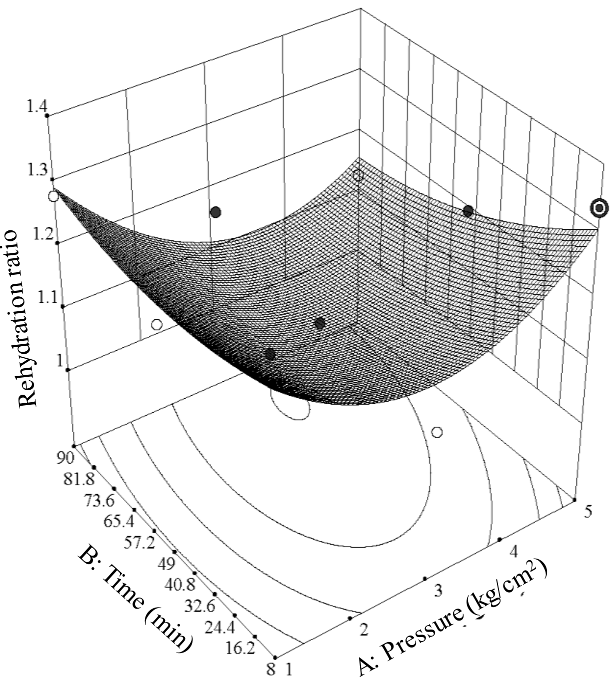

Figure 5
Model response surface graph for rehydration ratio

Table 4
Optimal solutions generated by DOE

Criteria	*Goal*	*Solution (optimized)*				
		1	*2*	*3*	*4*	*5*
Des.	*Max.*	0.68	0.46	0.46	0.46	0.46
Press.	*Min.*	1.01	4.16	4.23	4.09	3.91
Time	*Min.*	20.88	8	8	8	8
R. R.	*Max.*	1.27	1.22	1.23	1.22	1.21
P. S.	*Min.*	0.47	0.63	0.62	0.65	0.68

Note. Des. = Desirability; Press. = Pressure (kg/cm2); Time = Press time (min); R. R. = Rehydration ratio; P. S. = Pore size (mm); Max. = Maximize; Min. = Minimize.

Conclusions

This study demonstrates that achieving high-quality dried-frozen tofu with favorable physicochemical attributes, including rehydration ratio, internal pore size, and textural characteristics, is attainable through a carefully designed process. Specifically, freezing regular tofu at -20°C for a week, followed by a controlled thawing in warm water at 50°C for 30 min, and subsequent drying at 75°C until reaching a moisture content of 10%, yielded promising results.

Furthermore, our investigation reveals the pivotal influence of pressure and press time on the physicochemical properties of tofu. Notably, the observed effects are significant ($p<0.05$) and quadratic. Despite the resource-intensive nature of pressure treatments, we emphasize the potential for optimization through systematic experimental design, such as RSM. This approach enables the efficient fine-tuning of pressure and press time parameters to achieve optimal results, mitigating the associated costs and ensuring a more sustainable production process.

Our findings suggest that a judicious combination of pressure and press time, specifically within the 3.908-4.163 kg/cm^2 range for 8 min, can yield frozen tofu with consistently satisfactory physicochemical properties. This optimized approach enhances the final product's quality and underscores the feasibility of cost-effective and resource-efficient manufacturing through strategic experimental design. Considering these insights, our study contributes valuable knowledge for advancing tofu processing techniques, offering a practical pathway for producing high-quality dried-frozen tofu on a larger scale.

Acknowledgements

We extend our sincere gratitude to Dharan Multiple Campus for unwavering support and cooperation throughout our research work.

Compliance with Ethical Standards

Conflict of Interest

The authors declare no conflict of interest.

Ethical approval

This work did not involve any animal study.

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