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DEVELOPMENT OF AN EFFECTIVE METHOD OF MICROWAVE TREATMENT OF SUNFLOWER KERNEL TO INCREASE OIL EXTRACTION

Akzhol Suleimen
Master of Technical Sciences*
ORCID: https://orcid.org/0009-0008-6401-7537
Baurzhan Nurakhmetov
Doctor of Technical Sciences, Professor, First Vice-Rector
Almaty Technological University
Tole bi str., 100, Almaty, Republic of Kazakhstan, 050012
ORCID: https://orcid.org/0000-0002-5064-8687
Ardak Askarov
Corresponding autor
PhD, Assistant Professor*
ORCID: https://orcid.org/0000-0001-8813-1336
Yevgeniy Medvedkov
Doctor of Technical Sciences, Professor*
ORCID: https://orcid.org/0000-0002-7632-2300
Ilyas Nurakhmetov
Master of Technical Sciences
Department of Automation and Robotics**
ORCID: https://orcid.org/0009-0003-0934-8257
*Department of Machines and Apparatuses of Production Processes**
**Almaty Technological University
Tole bi str., 100, Almaty, Republic of Kazakhstan, 050012

The study focused on microwave processing of sunflower seeds and a unit for its implementation during the preparation stage for mechanical pressing. This unit intensifies the destruction of the kernel's cellular structure, increases oil yield, and maintains its quality within acceptable limits.

The aim was to increase the extraction of high-quality sunflower oil.

The design features of a pilot unit for microwave seed processing and the optimal parameters for microwave seed processing were determined.

It was established that maximum oil extraction without degrading its quality is achieved by using a gentle microwave processing mode, which prevents overheating, changes in the structure and chemical composition of the kernel, and increased oxidation processes. The unit was applied at a power of 500 watts for 150 seconds with a 42 mm layer of peeled sunflower seeds. With these values, the oil yield was approximately 57.4%. Uniform grain distribution within the processed layer was achieved by using a guide spiral and a rotating horizontal disk, which ensures uniform movement and height of the moving layer.

A distinctive feature of the obtained results is the use of a microwave processing unit consisting of a guide spiral, a rotating horizontal disk, and an experimental methodology using second-order rotatable planning to determine the relationship between oil yield and microwave power, duration, and seed layer thickness on the rotating disk surface.

These results can be scaled up for use in industrial vegetable oil production facilities for domestic consumption and increased potential exports

Keywords: sunflower, microwave processing, microwave radiation, mechanical pressing, oil yield, experimental planning, optimization

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1. Introduction

Oilseed crops are increasingly important in global crop production, providing raw materials for the food, feed, and bioenergy industries. Sunflower is one of the most widely grown crops, accounting for a significant share of vegetable oil production.

The Republic of Kazakhstan is demonstrating steady growth in sunflower seed production and is gradually becoming a significant player in the global oilseed market.

The development of the oilseed sector is accompanied by an accelerated expansion of processing and export capacity for finished products.

A critical step in the technological operations of vegetable oil production is heat-moisture treatment before pressing to increase oil yield.

A significant portion of energy expenditure is spent on heat treatment of the raw materials (convective drying and frying), which is often accompanied by uneven heating, the risk of localized scorching, darkening of the oil, increased acid and peroxide values, and partial degradation of natural antioxidants. In this regard, innovative methods for thermal treatment of oilseeds, including treatment in a microwave electromagnetic field, are generating growing interest.

Unlike traditional methods, microwave treatment ensures volumetric energy distribution, which accelerates heating, intensifies moisture removal, and reduces the duration of thermal exposure. However, due to insufficient research, this method has not yet been applied on an industrial scale.

Therefore, research into the scientific justification and practical application of microwave treatment of sunflower seeds is urgently needed.

2. Literature review and problem statement

Research into microwave processing of oilseeds has expanded significantly, driven by the need to improve energy efficiency and controllability of raw material pretreatment processes prior to mechanical oil extraction. It has been shown that microwave heating of sunflower seeds promotes the destruction of cellular structures and increases oil yield [1]. A study [2] found that increasing the duration of microwave processing increases oil yield and tocopherol content, but simultaneously accelerates oxidation processes and leads to an increase in acid and peroxide values. However, these studies were conducted under laboratory conditions on static samples and did not consider the technological limitations of continuous production processes, including issues of uniform heating and preventing localized overheating of the raw material.

In terms of raw material structure, separate studies have focused on the processing of peeled sunflower kernels. A study [3] demonstrated that removing the shell improves electromagnetic field penetration and promotes the formation of a porous structure, leading to a significant increase in oil yield. The same study noted the formation of polycyclic aromatic hydrocarbons and heterocyclic amines at elevated processing temperatures, emphasizing the need for strict thermal control. However, these studies primarily addressed the problem from a chemical perspective and did not propose technological solutions to ensure safe processing conditions under industrial conditions.

Comparative studies of microwave and convective heating showed that ultra-high-frequency processing provides faster volumetric heating of raw materials and allows for the production of a product with comparable sensory characteristics [4]. In [5], it was found that increasing microwave power intensifies oxidative degradation of lipids and degrades oil quality. The influence of ultra-high-frequency heating parameters on the formation of volatile aromatic compounds has also been confirmed experimentally [3]. However, these studies focused primarily on analyzing the characteristics of the final product and did not consider the interaction of ultra-high-frequency processing of dehulled sunflower seeds prior to mechanical pressing.

A number of studies have been devoted to combined pre-treatment methods, including ultra-high-frequency heating combined with enzymatic treatment. A study [6] demonstrated that this approach increases oil yield and enhances the antioxidant activity of the product. However, the proposed technology requires additional processing steps and a more complex process flow, which limits its applicability in continuous pressing lines for vegetable oil production. Thus, combined methods have high potential, but do not address the problem of integrating microwave processing into existing industrial processes.

Studies of other oilseed crops demonstrate similar patterns. A study [7] demonstrated that microwave pretreatment of rapeseed increases the nutraceutical content and improves oil yield. It was also found that microwave heating causes changes in the microstructure of rapeseed, contributing to increased oil recovery [8]. For pumpkin seeds, microwave-enzymatic treatment has been shown to increase the antioxidant activity of the oil [9]. A study [10] found an increase in oil yield and the content of biologically active compounds in milk thistle after microwave pretreatment. However, the results obtained for other crops cannot be directly transferred to sunflower due to differences in the anatomical structure and dielectric properties of the seeds.

While raw material properties have been shown to significantly impact heating efficiency [11], the behavior of a moving seed bed in a microwave field remains virtually unstudied. Despite the significant amount of accumulated data on the influence of microwave heating on oil structure and properties, which is also confirmed in review papers on modern oilseed pre-treatment methods [12, 13], most studies examine the processing process under static conditions. The influence of layer thickness and the nature of its mixing on the uniformity of heating and the efficiency of subsequent pressing remains insufficiently studied.

Thus, existing research primarily focuses on the chemical and qualitative characteristics of the oil, while the technological aspects of integrating microwave pre-treatment of sunflower seeds before mechanical pressing remain underdeveloped. Scientifically validated processing modes that take into account the distribution of electromagnetic energy in a moving seed bed, its thickness, and mixing dynamics are lacking. This limits the potential for the industrial implementation of microwave technologies in sunflower processing. Therefore, there is a need to conduct a comprehensive study of microwave processing of sunflower seeds under controlled layer motion conditions, followed by mathematical modeling of the effects of radiation power, processing time, and layer thickness on oil yield and quality parameters. This study will help bridge the existing gap between laboratory results and the requirements of industrial mechanical pressing technology.

3. The aim and objectives of the study

The aim of the study is to develop an effective method for microwave processing of sunflower kernels to enhance oil extraction while selecting the optimal seed layer thickness ratio. This will increase oil yield while meeting technological quality requirements.

To achieve this aim, the following objectives were set:

– to develop a mathematical model of the ultra-high-frequency processing of sunflower seeds and determine the optimal operating parameters (processing duration, microwave power, and seed layer height) to ensure maximum oil yield during subsequent mechanical pressing;

– to substantiate a rational seed layer thickness during microwave processing.

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of the study is the microwave treatment of sunflower seeds and the unit for its implementation during the preparation stage for mechanical pressing, which intensifies the destruction of the kernel's cellular structure, increases oil yield, and maintains its quality within acceptable limits.

The main hypothesis of the study is that microwave treatment of sunflower seeds under conditions of controlled movement and mixing of the layer can ensure more uniform heating of the material compared to static processing. It is assumed that optimization of parameters such as microwave radiation power, treatment duration, and seed layer thickness will enhance kernel structural changes, reduce internal resistance to oil release, and increase oil yield without significant thermal deterioration.

Assumptions:

– in a stationary seed layer, the microwave energy distribution is uneven;

– the movement and mixing of the layer help equalize the temperature field;

– the seed layer thickness significantly affects the uniformity of heating and the magnitude of temperature gradients;

– increasing the radiation power reduces the processing time but increases the risk of localized overheating.

Simplifications adopted:

– sunflower seeds are considered a homogeneous, free-flowing dielectric medium;

– differences in the size and shape of individual seeds are ignored;

– heat exchange with the environment is assumed to be uniform;

– the effect of humidity is taken into account indirectly through changes in the heating temperature regime.

4. 2. Experimental unit for ultrahigh-frequency processing

For the experiments, the authors developed and manufactured an experimental unit for ultrahigh-frequency processing of sunflower seeds [14] prior to pressing. A general view of the unit is shown in Fig. 1.

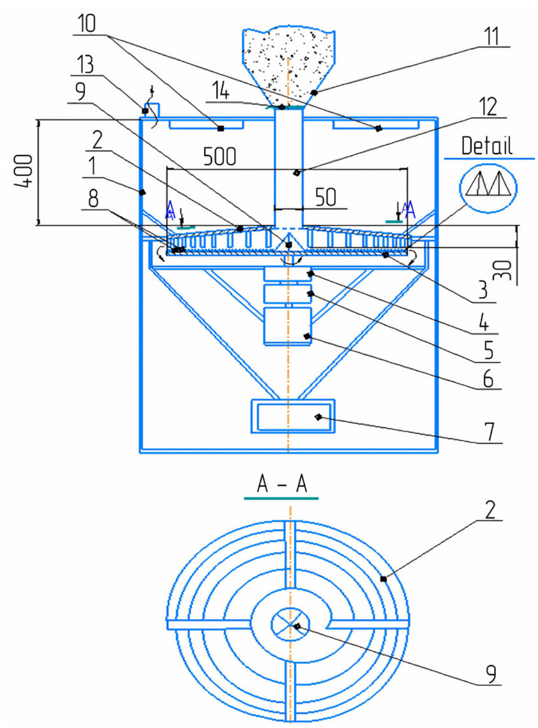

Fig. 1. Experimental unit for microwave processing of sunflower seeds before pressing: 1 – housing; 2 – fixed guide spiral; 3 – rotating disk; 4 – bearing with housing; 5 – gearbox; 6 – electric motor; 7 – discharge hopper; 8 – rough disk surface; 9 – conical product distributor; 10 – magnetrons for emitting microwaves; 11 – loading hopper; 12 – pipe for feeding the feedstock onto the disk surface; 13 – pipe with a check valve; 14 – gate valve

The unit consists of a cylindrical body with a horizontal rotating disk and a fixed guide spiral. The elements in contact with the seeds, as well as the internal wall of the unit, are made of dielectric materials, which prevents shielding of the microwave field. The seeds are fed through a loading hopper into the central part of the disc, where they are then moved toward the periphery by centrifugal force and a guide spiral.

The gap between the spiral and the disc is 1–2 millimeters, which corresponds to the average size of cleaned sunflower seeds and ensures their directional movement. The disc is rotated by a geared motor, and the speed is regulated by a frequency converter. The diameter of the disc and spiral is 500 millimeters. The guide spiral, located above the rotating disc, is shown in Fig. 2.

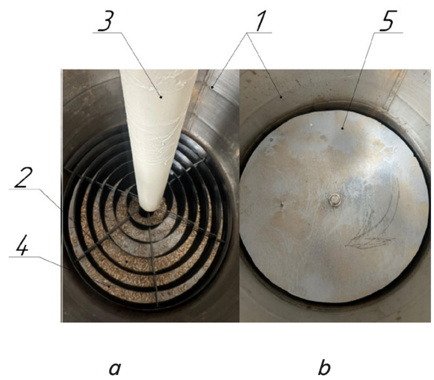

Fig. 2. Experimental unit: *a* – general view: 1 – housing; 2 – spiral; 3 – nozzle; 4 – sunflower seeds; *b* – rotating disk under the spiral; 5 – rotating disk

The unit design provides simultaneous exposure to an electromagnetic field and mechanical mixing of the layer, simulating the conditions of continuous industrial processing.

4. 3. Experimental methodology

Purified black sunflower seeds with a moisture content of 6% were used as raw material. Weighing was performed on an AS 310.X2 analytical balance (Radwag, Poland).

The seeds were fed into the unit's working area, where they were subjected to microwave processing with varying parameters:

– seed layer thickness: 8–42 mm;

– processing duration: 1–4 minutes;

– total power of the microwave generators (magnetrons): 200–800 watts.

The seed temperature after treatment was measured with a DT-8663 infrared pyrometer (CEM, China).

The exposure time was controlled by varying the disk rotation speed. The layer thickness was controlled by the position of the slide gate.

After microwave treatment, the seeds were sent for mechanical pressing. They were pressed using an ODM-01 screw oil press (China) at a screw speed of 50 min^{-1}. The press body temperature was maintained in the range of 90–100°C.

Oil yield was determined gravimetrically as the ratio of the mass of oil obtained to the mass of the original seeds. The selected parameter ranges allowed to study the influence of microwave radiation power, treatment duration, and layer thickness on seed structural changes and the efficiency of subsequent oil extraction.

The experimental unit used simulates the microwave pretreatment of sunflower seeds under conditions similar to continuous industrial processing, where the material is in motion and subjected to the simultaneous action of an electromagnetic field and mechanical mixing. This allows to study the influence of ultra-high-frequency processing modes on the efficiency of subsequent mechanical pressing, taking into account real process factors, including layer thickness and dynamics.

4. 4. Experimental design and data processing

The experimental studies were conducted using mathematical experimental design methods, which ensure the generation of statistically valid models with a minimum number of experiments.

Experimental data processing was performed using STATISTICA 10 software (StatSoft, USA). The statistical significance of the regression coefficients was assessed using the Student's t-test, and the adequacy of the model was assessed using the Fisher exact test.

5. Results of the experimental microwave treatment of sunflower seeds

5. 1. Determining optimal process conditions

To determine the optimal parameters for the microwave treatment of dehulled sunflower seeds followed by pressing, studies were conducted using a rotatable experimental design method, which allows for the most accurate mathematical description of the process.

The following were selected as the main variable factors: x_1 – microwave treatment duration, t (seconds); x_2 – microwave power, N (watts); x_3 – seed layer height on the surface of a horizontal rotating disk, h (mm). The selected factors are compatible with each other and uncorrelated.

The selected factors varied within specified intervals and were coded using a standard method with levels of –1, 0, +1 and star points of ±1.682. The total number of experiments was $N=20$, including $N_0=6$ experiments in the center of the design. The coding of intervals and levels of factor variation is presented in Table 1.

Table 1

Coding of intervals and levels of factor variation

Factors		Variation levels					Variation intervals
Natural	Coding	–1.68	–1	0	+1	+1.68	
Microwave treatment duration (t, s)	x_1	66	100	150	200	234	50
Microwave power (N, W)	x_2	198	320	500	680	802	180
Thickness or height of seed layer on the surface of a horizontal disk (h, mm)	x_3	8	15	25	35	42	10

The response function Y is oil yield, grams.

The experimental design matrix for the second-order rotatable design, the Box design, is presented in Table 2.

The dependence of oil yield on the studied factors was approximated by a second-order full quadratic regression model

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + \\ + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2.$$

Table 2

Rotatable design matrix for the experimental study of microwave treatment of sunflower seeds before pressing

No.	Modifiable parameters						Output parameters	
1	Coded			Physical			Oil yield Y, grams	
Experiment No.	x_1	x_2	x_3	x_1	x_2	x_3	Experiment	Calculation
1	+	+	+	200	680	35	36.8	42.0951
2	+	+	–	200	680	15	47.9	49.9749
3	+	–	+	200	320	35	46.1	48.1835
4	+	–	–	200	320	15	52.5	53.9633
5	–	+	+	100	680	35	51.3	53.1886
6	–	+	–	100	680	15	50.5	51.7684
7	–	–	+	100	320	35	45.6	46.8769
8	–	–	–	100	320	15	45.3	43.3568
9	–1.682	0	0	66	500	25	48.2	48.3351
10	1.682	0	0	234	500	25	52.8	47.9256
11	0	–1.682	0	150	198	25	46.1	46.0034
12	0	1.682	0	150	802	25	52.6	47.9573
13	0	0	–1.682	150	500	8	53.8	53.7136
14	0	0	1.682	150	500	42	54.7	50.0471
15	0	0	0	150	500	25	54.3	54.3133
16	0	0	0	150	500	25	54.2	54.3133
17	0	0	0	150	500	25	54.0	54.3133
18	0	0	0	150	500	25	54.1	54.3133
19	0	0	0	150	500	25	54.17	54.3133
20	0	0	0	150	500	25	54.3	54.3133

Let's rename the coded values of factors x_1, x_2, x_3 to the named values t (seconds); N (watts); h (mm)

$$x_1 = \frac{\text{ô}-100}{50}, \quad x_2 = \frac{N-500}{180}, \quad x_3 = \frac{h-15}{10}.$$

As a result of substitution, let's obtain the equation

$$Y = 54.31 + 0.12x_1 + 0.58x_2 + 1.09x_3 + 3.10x_1x_2 + \\ + 2.33x_1x_3 + 0.53x_2x_3 + 2.19x_1^2 + 2.59x_2^2 + 0.86x_3^2.$$

For clarity, graphical dependences of oil yield on microwave power and processing duration, microwave power and seed layer thickness, and on duration and seed layer thickness were plotted (Fig. 3–5).

To assess the significance of the coefficients in the resulting equation, it is possible to calculate the Student's t-test using the equation

$$t_i = \frac{|b_i|}{S_\beta},$$

where S_β – the standard error of the regression coefficients

$$S_\beta = \sqrt{\frac{S_i^2}{N}},$$

which, for a total number of experiments $N=20$, is $S_\beta = 0.0261$.

With degrees of freedom $f_r = N_0 - 1 = 5$ and a significance level of $\alpha = 0.05$, the calculated tabular value of the Student's t-test is $t_{table} = 2.57$.

Based on the analysis of the obtained data, it is possible to conclude that the intercept, linear, and quadratic regression coefficients are statistically significant (Table 3). Some of the cross-terms do not have a significant effect on the oil yield and can be excluded without losing the adequacy of the model.

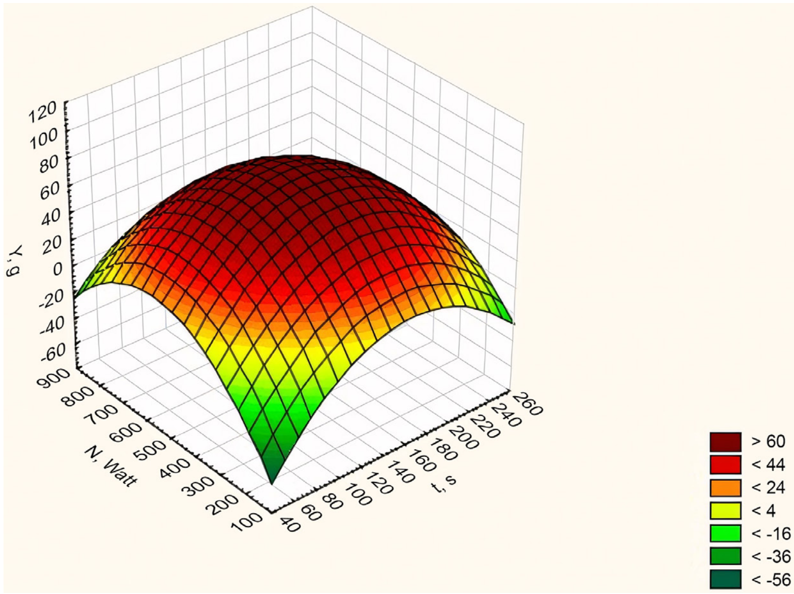

Fig. 3. Oil yield (Y) versus treatment duration t (seconds) and microwave power N (watts)

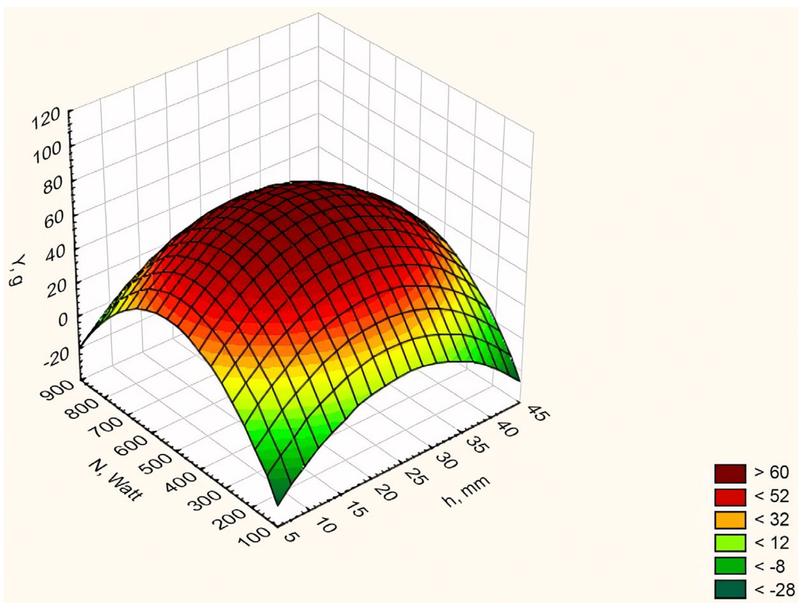

Fig. 4. Oil yield (Y) versus seed layer thickness h (millimeters) and microwave power N (watts)

Table 3

Testing the significance of the regression coefficients using the Student's t-test

Coefficient	Physical meaning	$t_{calculated}$	T_{table}	Conclusion
b0	Free meaning	>>2.57	2.57	Significant
b1	Linear effect x_1	>2.57	2.57	Significant
b2	Linear effect x_2	>2.57	2.57	Significant
b3	Linear effect x_3	>2.57	2.57	Significant
b12	Interaction $x_1 x_2$	<2.57	2.57	Insignificant
b13	Interaction $x_1 x_3$	<2.57	2.57	Insignificant
b23	Interaction $x_2 x_3$	≈2.57	2.57	Conditionally significant
b11	Quadratic effect x_1^2	>2.57	2.57	Significant
b22	Quadratic effect x_2^2	>2.57	2.57	Significant
B33	Quadratic effect x_3^2	>2.57	2.57	Significant

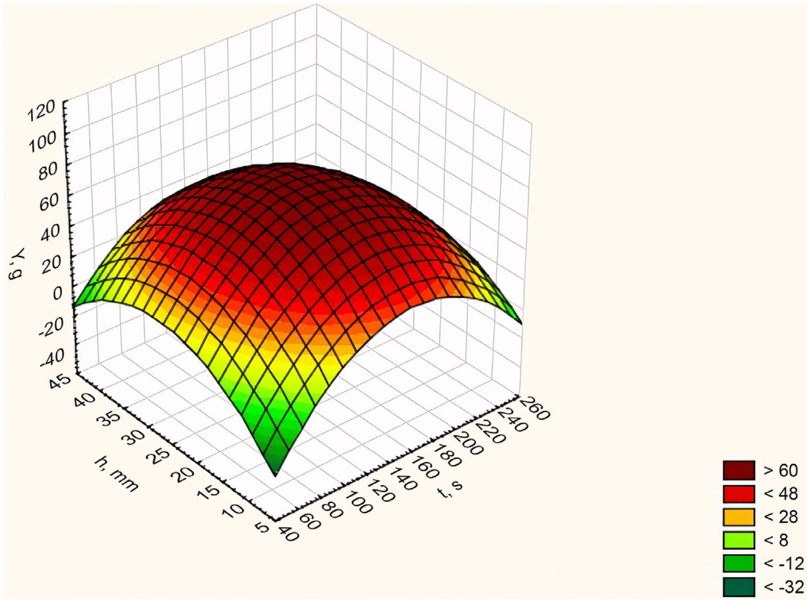

Fig. 5. Oil yield (*Y*) versus treatment duration *t* (seconds) and seed layer thickness *h* (millimeters)

Coefficients b_{12} and b_{13} are insignificant and can therefore be excluded from the equation.

The adequacy of the model was assessed by comparing the calculated Fisher exact test value with the tabulated value.

The calculated Fisher exact test was determined from the equation

$$F_{calc.} = S_a d^2 / S_r^2,$$

where $S_r^2 = 1/(N_0 - 1)\Sigma(Y_{0J} - \bar{Y}_0)^2$ – the reproducibility variance.

Process reproducibility was assessed based on the results of six replicate experiments in the center of the design, $N_0 = 6$. The average oil yield in the center of the design was $\bar{Y}_0 = 54.18$ g. The numerical value of the reproducibility variance is $S_r^2 = 0.0136\ g^2$.

$S_a d^2 = 1/(N-1)\Sigma(Y_{iexp} - Y_{icalc})^2$ – the variance of the model adequacy.

Taking $N = 14$ – the number of unique experimental points, assuming the exclusion of six replicate experiments in the center of the design, and $p = 10$ – the number of model coefficients, it is possible to obtain the calculated value of the adequacy variance of $S_a d^2 = 0.041\ g^2$.

Using the obtained values of the model adequacy variance and the reproducibility variance, it is possible to obtain the calculated Fisher's exact test value of $F_{calc} = 3.01$. Since $F_{calc} < F_{table} = 5.19$ at $\alpha = 0.05$, the regression model is adequate.

Thus, excluding repeated central experiments, the model is considered adequate, with the vast majority of regression coefficients being significant. This allows to conclude that the resulting model is suitable for analyzing and optimizing microwave treatment modes for sunflower seeds within the studied range of factors.

To determine the microwave processing parameters that ensure maximum oil yield, it is possible to use the Derringer-Sewich method: single response (Y – the oil yield), target is maximum, and construct a generalized desirability function D

$$D = d(Y).$$

To determine reasonable technological limits for oil yield, it is possible to adopt a lower limit of $L = 35\%$ (the minimum, based on experimental results, is 36.8%) and an upper limit of $U = 55\%$ (based on experimental results, 57.7%) to avoid $d = 0$ or 1.

Let's use the linear form $s = 1$:

$$d(Y) = \begin{cases} 0, Y \le L, \\ \dfrac{Y - L}{U - L}, L < Y < U, \\ 1, Y > L, \end{cases} \text{ or } d(Y) = \begin{cases} 0, Y \le 35, \\ \dfrac{Y - 35}{20}, 35 < Y < 55. \\ 1, Y > 55. \end{cases}$$

For the obtained results from 20 experiments, it is possible to obtain the desirability function values, rounded to 3 decimal places (Table 4).

Table 4

Desirability function values based on experimental results

Experiment No.	*Y*, %	*d* (*Y*)
1	36.80	0.090
2	47.90	0.645
3	46.10	0.555
4	52.50	0.874
5	51.30	0.815
6	50.50	0.775
7	45.60	0.530
8	45.3	0.515
9	48.20	0.660
10	52.80	0.890
11	46.10	0.555
12	52.60	0.880
13	53.80	0.940
14	54.70	0.985
15	54.30	0.965
16	54.20	0.960
17	54.00	0.950
18	54.10	0.955
19	45.17	0.959
20	54.30	0.965

For the same response, the generalized desirability function D for the entire system is determined by

$$D(x_1,x_2,x_3)=d(Y(x_1,x_2,x_3)),$$

where $Y(x_1, x_2, x_3)$ is defined by the resulting second-order regression equation.

Maximum desirability (closest to 1) is achieved in the experiments with the highest oil yield (14^{th}–20^{th}).

The desirability function plot for the experiments is shown in Fig. 6.

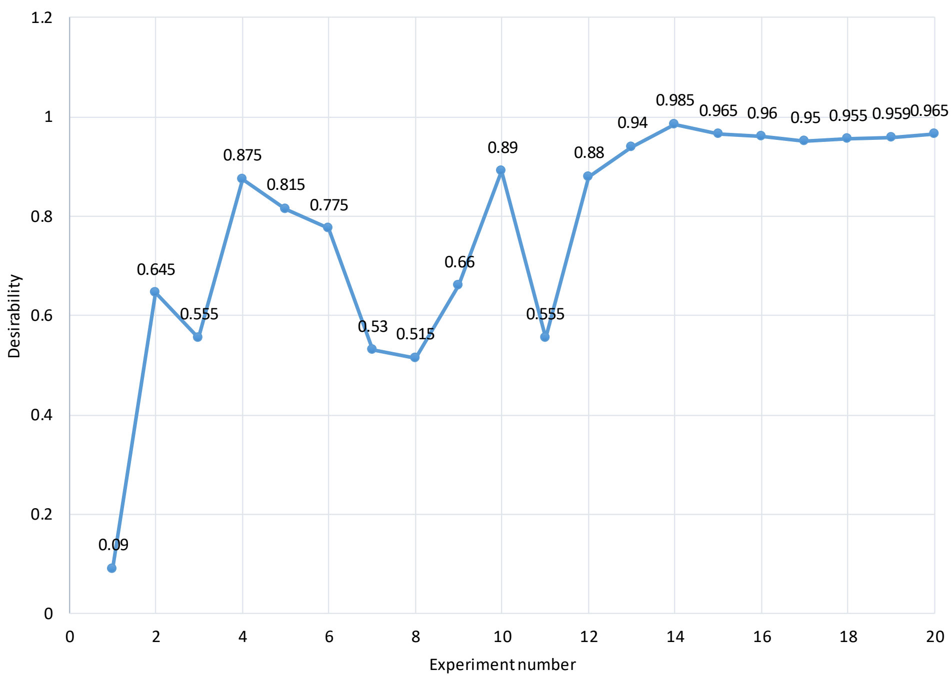

Fig. 6. Desirability graph for the experiments

To calculate the overall quality of the entire experiment, let's take the geometric mean across all experiments with an acceptable value

$$D_{tot}=(\Pi d_i)^{\frac{1}{m}},$$

where m – the number of experiments with $d_i > 0$.

Based on the experimental results, it was found that $D_{total} \approx 0.71$.

5. 2. Justification for a rational seed layer thickness during microwave treatment

Based on the experimental data from 20 experiments, the highest oil yield is observed in experiments 14–20. However, in experiments 15–20, the seed temperature after microwave treatment exceeds the standard and is 115°C or higher, while the acid number, peroxide number, and tocopherol exceed international standards. This is also explained by the fact that the layer thickness in these experiments was 25 mm. This, on the one hand, reduces the productivity of the system. In Experiment 14, with the highest seed layer thickness, the temperature after microwave treatment was approximately 95°C, which meets standards. The acid value, peroxide value, and tocopherol content in this experiment also meet the international standard for first-grade sunflower seeds. Uniform distribution of microwave radiation and the temperature field within the intergranular space are ensured by the rational design of the horizontal rotating disk and the fixed guide spiral, which ensures effective mixing of the seeds during the process. Taking into account the seed temperatures before pressing, as well as the acid value, peroxide value, and tocopherol content in the oil, the effective seed layer thickness is 42 mm. This selected thickness ensures high system throughput and the specified process efficiency. Oil temperatures after pressing in each experiment are listed in Table 5.

Table 5

Seed temperature after microwave treatment and before pressing

Experiment No.	Microwave power, W	Seed temperature, °C after microwave treatment	Oil temperature, °C after pressing
1	2	3	4
1	680	130	116.0
2	680	159	133.4
3	320	81	86.6
4	320	98	96.8
5	680	110	104.0
6	680	140	122.0
7	320	65	77.0
8	320	78	84.8
9	500	81	86.6
10	500	150	128.0
11	198	62	75.2
12	802	156	131.6
13	500	125	113.0

Continuation of Table 5

1	2	3	4
14	500	95	95.0
15	500	115	107.0
16	500	116	107.6
17	500	118	108.8
18	500	120	110.0
19	500	115	107.0
20	500	117	108.2

Since continuous monitoring of the oil temperature at the press outlet in each experiment was difficult, a calculated estimate based on the concentrated heat capacity model was used for subsequent analysis. The oil temperature at the press outlet was determined using the expression

$$T_{oil} = T_{press} + \alpha\left(T_{seed} - T_{press}\right),$$

where $T_{press} = 95°C$ is the average temperature of the press working parts; T_{seed} is the seed temperature after microwave treatment; and $\alpha = 0.6$ is the thermal equalization coefficient adopted based on preliminary estimates.

6. Discussion of the results of the study of design parameters and modes of microwave seed treatment

The increased oil yield after microwave pretreatment of sunflower seeds (Table 2, Fig. 3–5) is explained by the combined effect of volumetric electromagnetic heating and continuous mechanical mixing of the seed layer in the developed unit (Fig. 1, 2). Microwave energy causes intense internal heating of moisture within the cells, which leads to partial destruction of the cell walls and weakening of the structural matrix of the kernel. As a result, the resistance of the material during subsequent mechanical pressing decreases, contributing to increased oil yield.

Unlike most laboratory studies, where treatment is carried out in a fixed bed, the proposed unit ensures continuous radial movement and mixing of the seeds using a rotating disk and a fixed guide spiral. This design (Fig. 1, 2) promotes a more uniform temperature distribution across the layer thickness and reduces the likelihood of localized overheating. The stabilizing effect of layer movement is indirectly confirmed by the temperature data (Table 5), as well as the statistical adequacy of the resulting regression model.

The rational seed layer thickness of 42 mm can be interpreted as a compromise between the depth of microwave energy penetration and internal heat redistribution. At thinner thicknesses of 8 and 15 mm, overheating of the upper layers was observed (Table 5), potentially degrading oil quality.

At greater thicknesses, the field efficiency decreases and the lower layers are partially shielded, reducing the effectiveness of structural changes. Thus, the optimum identified by the regression model and the desirability function (Table 4) has both physical and technological justification. One study reported that microwave cooking of sunflower seeds (500 W for 12 min) did not affect the fatty acid composition of sunflower oil [15], while another study found that the percentage of linoleic acid in sunflower seeds decreased after microwave cooking, while that of oleic acid increased (500 W for 5–15 min) [1]. Microwave cooking of oilseeds may promote the transport of oil droplets across cells by damaging the lipoprotein membrane, which increases the release of tocopherols from the oilseed structure into oil [16]. On the other hand, microwave cooking of sunflower seeds (500–600 W, 9–15 min) resulted in the loss of approximately 20–30% of tocopherols in sunflower oil due to thermal oxidation [17]. Apparently, the effect of microwaves on lipid oxidation and nutritional composition of oilseed product depends on the power and time of processing of oilseeds, which requires further study.

The optimal combination of microwave power (approximately 500 watts) and processing time (approximately 150 seconds) ensures sufficient destruction of the kernel's cellular structure without entering the zone of intense thermal degradation. At higher power and time values, seed temperature increases significantly (Table 5), which can enhance lipid oxidation processes, as has also been noted in studies by other authors on microwave processing of oilseeds.

Compared to existing approaches, a distinctive feature of the proposed method is the combination of microwave heating with controlled movement of the seed layer. Most published studies primarily examine chemical changes during static processing, whereas this paper emphasizes the technological feasibility of the process. The developed unit thus represents a transition from laboratory microwave processing to a process flowsheet potentially suitable for integration into continuous mechanical pressing lines. The obtained results are valid within the studied factor ranges (power 200–800 watts, duration 1–4 minutes, layer thickness 8–42 mm) and for sunflower seeds with similar physical and dielectric properties. Outside these limits, the temperature and electromagnetic field distribution may change, requiring refinement of the model.

Limitations of the study include direct measurements of the temperature distribution within the moving layer, as well as a limited set of oil quality indicators. Furthermore, the energy efficiency of the process was assessed indirectly. Future studies would benefit from electromagnetically induced structural changes in the kernel combined with more uniform energy distribution through mechanical mixing of the layer, which fundamentally distinguishes the proposed technology from traditional methods of thermal pre-pressing of sunflower seeds.

7. Conclusions

1. Using the second-order rotatable experimental design (Box design), a quadratic regression model was obtained describing the relationship between oil yield Y and microwave treatment duration t, microwave power N, and seed layer thickness h. Student's t-tests established the statistical significance of the intercept, linear, and quadratic effects, while Fisher's exact test confirmed the adequacy of the model with-

in the studied range of factors. Using the Derringer-Suwich desirability function, optimal combinations of parameters were determined to increase oil yield; the integrated quality assessment of the experimental domain was $D_{total} \approx 0.71$.

2. It has been shown that the maximum oil yield values obtained in a number of experiments cannot be considered rational when taking into account process quality limitations: at a thinner layer thickness (e.g., $h = 25$ mm), seed overheating (up to 115°C and above) and oil parameters (acid number, peroxide value, tocopherols) outside the specified limits are observed. A comparison of seed temperatures after microwave treatment and the calculated oil temperature at the press outlet allowed to substantiate a rational layer thickness of $h = 42$ mm, which ensures acceptable temperature conditions (approximately 95°C in experiment 14) and meets oil quality requirements while simultaneously increasing plant productivity.

Conflict of interest

The authors declare that they have no conflicts of interest with respect to this study, whether financial, personal, proprietary, or otherwise, that could influence the study and its results presented in this article.

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The study was conducted without financial support.

Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of this work.

Authors' contributions

Suleimen Akzhol Maksatuly: Investigation, Data curation, Data processing, **Nurakhmetov Baurzhan Kumargaliyevich**: Supervision; **Askarov Ardak Dakharbekovich**: Conceptualization, Methodology, Writing – review & editing; **Medvedkov Yevgeniy Borisovich**: Supervision, Methodology; **Nurakhmetov Ilyas** – Formal analysis, Data analysis, Statistics.

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