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Development of a small-size processing line for production of safflower oil

Maigul Mursalykova[1] | Bauyrzhan Iskakov[2] | Mukhtarbek Kakimov[2] | Gulmira Zhumadilova[1] | Assem Shulenova[3]

[1]Department of Technological Equipment and Mechanical Engineering, Shakarim University of Semey, Semey, Republic of Kazakhstan

[2]Department Technology of Food and Processing Industries, S. Seifullin Kazakh Agrotechnical University, Astana, Republic of Kazakhstan

[3]Faculty of Engineering and Technology, Innovative Eurasian University, Pavlodar, Republic of Kazakhstan

Correspondence
Maigul Mursalykova, Department of Technological Equipment and Mechanical Engineering, Shakarim, University of Semey, Semey 071412, Republic of Kazakhstan.
Email: mmursalykova@yahoo.com

Abstract

There is growing interest in exploring new types of cultivated plants that offer unique health benefits. Safflower is a promising plant nutrition resource that has gained popularity in Kazakhstan and worldwide. However, one of the pressing issues is improving the consumption pattern of food products, including vitamins and microelements. This article aims to develop a small-scale processing line for safflower oil production in small enterprises of the cereal-processing industry. The primary focus is on purifying safflower from impurities and husks, as well as compressing and centrifuging the oil raw material for high-quality and biologically valuable product. The authors developed a processing line consisting of a sheller-compress and a centrifuge of original constructions for separating husks from the kernel and compressing and centrifuging the oil raw material. The process combines husking, compressing, filtration, and sedimentation to ensure primary purification of plant oils and the removal of mechanical impurities. The production of safflower oil has become an urgent task due to its rich composition of vitamins and phospholipids. The newly developed processing line ensures the production of high-quality safflower oil and has great potential for small enterprises in the cereal-processing industry. The article highlights the importance of primary purification of plant oils and its impact on the quality of the final product.

Practical applications

The following conclusions emerged from the research. The relevance of fat oil growing, including signs of increased popularity of safflower oil in Kazakhstan and in the world has been studied. Various types (husking, compressing, sedimentation, centrifuging and filtering) of primary purification of safflower and purification of oil from mechanical impurities have been investigated. The dependence of extraction of pressed safflower oil on the speed of rotation of the filter and settling rotor and the equipment structure itself has been studied. The sheller-compress for purification of safflower has been developed to combine husking and compressing processes to increase the oil content of the processed oil raw material and the productivity of the processing equipment. The centrifuge is designed for primary purification of safflower oil from mechanical impurities, allowing to combine the sedimentation and filtering processes due to rotors and to obtain purified safflower oil. The problem of intensification of the purification process is characterized by the ratio of different defined parameters. As a result, optimum parameters were determined and a processing line was developed with the use of a sheller-compress and a centrifuge with a filtering and pre.

KEYWORDS
centrifuge, cereal-processing industry, oil production, plant oil, purification, sheller

1 | INTRODUCTION

To date, the fat-and-oil complex of the Republic of Kazakhstan is an integrated system of technologically and economically interconnected branches and sub-branches of crop production, processing industry, trade and public catering, machine industry for these branches, as well as other branches and enterprises of the agricultural sector, production and market infrastructure, the common objective is to market plant oil to saturate the market and meet the needs of the state for this important product (APK-Inform, 2022). Improving the structure of food consumption, including vitamin, micronutrient and biologically active additives, is a compressing issue (Message from the President of the Republic of Kazakhstan K.-Zh, 2021). Recently, there has been an increased interest in the application of new types of cultivated plants, which differ from the traditional feature complex and health properties. Among the promising plant nutrition resources, safflower plays an important role, which in the future can compete with the traditionally known oil crops. Safflower is an agricultural crop with an ancient history: for many centuries this plant was used to produce both dye from petals and oil from seeds. Safflower oil is a unique product of plant origin, the chemical composition of which allows it to be used for medical, cosmetic, food production. Taking into account the biological values and rich composition of vitamins and phospholipids, production of safflower oil is currently a topical task (Nesterova et al., 1999).

The production of plant oils involves various techniques that affect the processed raw materials. Mechanical processes play a significant role in this technology. Seed purification, destruction and separation of the fruit and seed coats from the corcule and endosperm, shredding of the kernel, and its intermediate products are predominantly mechanical processes that prepare the material for intense physicochemical transformation (Tlevlessova et al., 2023). In modern production, the compaction method is one of the primary methods of plant oil production (Nogales-Delgado et al., 2021). Most modern compresses are designed to compress oil from individual crops, and reconfiguring this equipment for other crops is difficult. If it is possible, the oil compressing takes place less efficiently. In small-scale production conditions, a universal compressor is needed to compress oil from both low- and high-oil crops (Kurmanov et al., 2014; Parfenova et al., 2003).

Safflower oil is a multicomponent polydisperse liquid system that includes protein and non-protein mechanical impurities. Apart from glycerol and related substances, these impurities contribute to the development of various processes of oil deterioration. Therefore, it is necessary to remove them as quickly as possible. To achieve this goal, various methods are used, such as sedimentation, centrifugation, and filtration (Bhadre et al., 2022; Chugh et al., 2022). The process line developed by combining husking, compressing, filtration, and sedimentation processes will speed up the primary purification process of safflower husks, as well as the purification of oil from mechanical impurities. As a result, the number of technological operations can be simplified, and the cost of inter-operational transportation and labor costs can be reduced, and the efficiency of oil use can be increased. Currently, there is no equipment available for simultaneous purification of safflower husks, compressing, filtering, and sedimentation of oil, and existing analogs only work in one direction. Therefore, the object of the study is safflower, including its physical and mechanical properties and aerodynamic parameters, while the subject of the study is the process of separating the husks from safflower, compressing the oil raw material, and purifying the oil from mechanical impurities by centrifugation through the combination of husking, compressing, filtration, and sedimentation processes (Kairbayeva et al., 2022; Shcherbakov & Lobanov, 2012).

The aim of the work is the primary purification of safflower from husks, the compressing of oil raw material, as well as the purification of oil from mechanical impurities by centrifugation by combining the husking, compressing, filtration, and sedimentation processes.

2 | MATERIALS AND METHODS

On the basis of the results of theoretical and experimental studies of the process of production of safflower oil, a processing line of this oil crop was developed. The presented small-sized line includes a storage hopper for purified safflower seeds, a sheller-compress, a centrifuge for filtration, and sedimentation, a hydrator, a neutralizer, a vacuum washer, a deodorant, a receiver for refined deodorized oil, vacuum pump, steam generator, heat generator, filter compress. Safflower seeds are fed into the storage hopper, where all storage modes and parameters must be observed (temperature, humidity). Safflower grain from the storage hopper is fed through the measuring hopper to the conveyor and weighed on automatic scales. The safflower seeds are then fed into the sheller-compress where heavy and light impurities are removed. The purified seeds are sent to a special fan separator, where they are separated from the husks and undergo another purification phase. After purification, the seeds are fed into the screw extruder to extract the oil.

After compression, the oil undergoes primary purification processes to remove various mechanical impurities. The process starts with settling pre-pressed oil in a capacitor to remove large mechanical

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impurities for 15–20 min, resulting in a nonfat impurity amount of 10% before sedimentation and 0.3%–0.5% after sedimentation. The oil is then filtered to remove small mechanical impurities, which purifies impurities resulting in a nonfat impurity amount of 0.3%–0.5% before filtration and 0.05% after filtration. After primary refining, unrefined safflower oil can be obtained, but if refined oil is desired, additional physicochemical refining is necessary. The physicochemical processing involves hydration, neutralization, bleaching, and deodorization processes. During hydration, the mixer container is pre-cleaned and then filled with safflower oil mixed with warm water and salt. The mixture is heated to 100°C using a heat generator and mixed for 15 min at a rate of 3–4 r.p.m. This process purifies safflower oil from phosphates and some hydrophilic substances.

In the neutralization tank, the oil is purified of free fatty acids, partially of flavoring and coloring substances, phospholipids, small amounts of wax and carbohydrates. Safflower oil is mixed and heated up to 65°C. Then, an alkaline solution and warm water are added in a quantity calculated according to known formulas. The mixer is switched off when safflower granules begin to settle in safflower oil and is proceeded sedimentation within 6 h after the neutralization process is completed. Safflower oil, treated with alkaline solution, is then bleached. Bleaching is the process of contact of safflower oil with sorbents. As a result, safflower oil whitens and leads to the destruction of fat-soluble pigments, that is, carotenoids, chlorophylls, carcinogenic compounds, soaps, oral and mucous substances (Gutyj et al., 2017). After the bleaching process, the safflower oil enters the frame filter and is purified of the adsorbent (Parfenova et al., 2003). Bleached oil undergoes final physicochemical treatment – deodorization. Its purpose is to eliminate low molecular acids, aldehydes, ketones and other volatile substances that affect the smell and taste of oil. When deodorizing, a vacuum is created in the tanks, a mixer and a steam generator are included. The vapor pressure of the steam generator shall not exceed 0.3 MPa. When the temperature in the tank reaches 180°C, it is necessary to turn on the vacuum pump. Volatile substances are washed out of the oil, purified of various impurities and stored in a drip-collector. After deodorization, the safflower oil passes through the fine filter and accumulates in the finished product storage tank. After the completion of all processes of the safflower oil processing line (Figure 1), get refined deodorized safflower oil. The finished product enters the packaging and filling line and is bottled.

3 | RESULTS AND DISCUSSION

3.1 | Description of experimental sheller-compress for husking and safflower oil compressing

A special place in the technological processing of safflower oil, including in the primary purification process, is occupied by the husking process (Deviren & Aydın, 2023; Hanif et al., 2023; Mursalykova et al., 2023). Purification of safflower seeds before entering the pressing area is very difficult and important (Pari et al., 2020). Pre-separating the husk from the kernel contributes to increasing the oil content of the processed oil raw material, the raw material is released from the low oil components and the relative oil content in it increases.

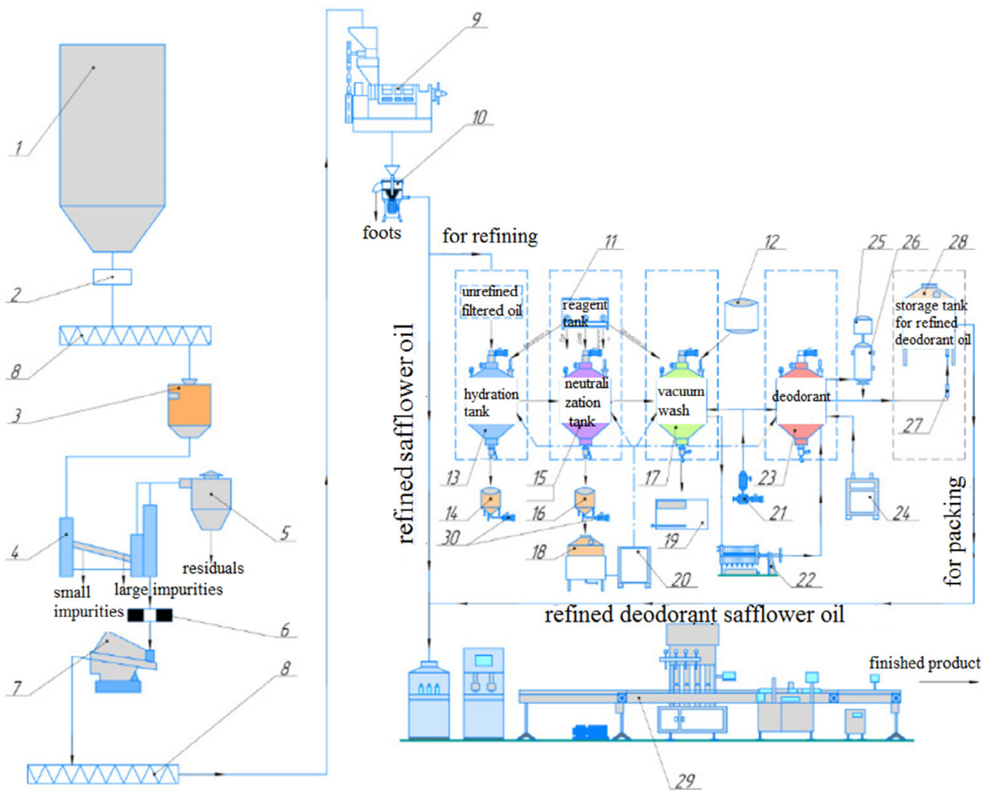

FIGURE 1 Process flow diagram of safflower oil processing line. 1 – safflower seed storage hopper; 2 – dispenser; 3 – automatic scales; 4 – separator; 5 – storage hopper for impurities; 6 – magnetic separator; 7 – rock separator; 8 – conveyor; 9 – sheller-compress; 10 – centrifuge for filtration, and sedimentation; 11 – reagent tank; 12 – bleaching tank; 13 – hydration tank; 14 – sediment tank; 15 – neutralization tank; 16 – soap stock tank; 17 – vacuum wash; 18 – soap stock storage tank; 19 – oil catcher; 20 – heat generator; 21 – vacuum pump; 22 – frame filter; 23 – deodorant, 24 – steam generator; 25 – storage tank of foreign objects; 26 – scrubber; 27 – filter; 28 – storage tank for refined deodorant oil; 29 – packing and filling line of safflower oil; 30 – pump.

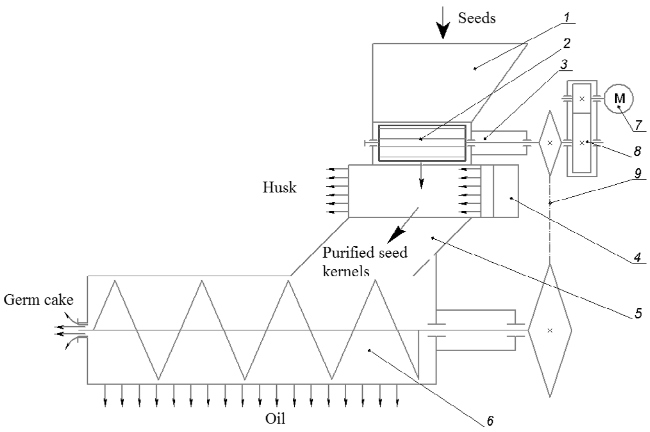

FIGURE 2 The structural scheme of sheller-compress for oil separation. 1 – bin; 2 – sheller; 3 – roller-type mechanism; 4 – fan separator; 5 – tray; 6 – screw extruder; 7 – electric moto; 8 – reducer; 9 – chain transmission.

At the same time, the productivity of the equipment is increased, as the volume of machines and apparatuses is not loaded with ballast low-oil material – husk. When separating husks, lubricants rich in wax and wax-like tallows do not fall into the market grade oil. In order to ensure a high degree of separation of husks from the kernel, a sheller-compress for separation of safflower seed oil was developed (Figure 2). This equipment is used in the fat and oil industry in the conditions of mini-production workshops.

The experimental sheller-compress includes bin 1, sheller 2, roller-type mechanism 3, fan separator 4, tray 5, screw extruder 6, electric motor 7, reducer 8, chain transmission 9 (Figure 2). Safflower seeds enter the bin and are transported to the sheller where, under the action of centrifugal force, through the guiding channels of the surface of the roll, are accelerated and, breaking through the windows of the roll, impact on the elastic coating located on the inner side of the deck. The husk of the seed is destroyed. Then the grain mass is uniformly fed into the fan separator. Fan separator cleans grain from large, small and light impurities. Purified seed kernels are supplied to the screw extruder where the oil is compressed and expressed (Havrysh et al., 2020).

The efficiency of hulling is achieved by the surface distribution of the impact energy over the kernel, as opposed to the impact on the hard surface, where the particle is in contact with the deck, causing the breakdown of the seeds (Mushtruk et al., 2022; Yesilyurt et al., 2020; Zanetti et al., 2022). Since the energy is distributed on the surface of the seed, the rate at which it bounces off the deck is much lower than when it hits a hard surface, which means that there is no further impact on the incoming product, which, in turn, preserves the integrity of the kernel and affects the quality of the peeled product (Nagovska et al., 2018).

In the oil compress, the prepared vegetable raw material is compressed to the required condition by the screw shaft coils to obtain oil, which is discharged into the crude oil tank via the grain slits, a cake is pushed through an additional pressure control unit in the grain chamber, simultaneously being pelletized, and the adjustment of each unit allows in each composite grain chamber to ensure the optimal mode of obtaining the maximum amount of oil (Askarov et al., 2022; Baiysbayeva et al., 2021).

3.2 | Calculation method and shelling mechanism of oilseeds

The analysis of the operation of the towpath dehuller led to the need to build the work of the sheller on the basis of a single impact with immediate removal of husking products from the scope of its working parts. Structurally this method is formed, as a rule, in the form of a turbine, the blades of which throw the seeds on an inclined smooth deck; reflecting from it, the husk leaves the machine (Fats and oils–Safflower oil, 2021; Shcherbakov & Lobanov, 2012). The following equations are given for the absolute, relative speed of the seed movement and for the angle, which is the vector of the seed velocity in the horizontal plane with the normal to the deck surface:

$$v_{abs} = \sqrt{2}\omega x \sqrt{f^2 - f\sqrt{f^2+1} + 1}, \tag{1}$$

$$v_{rel} = \omega x \left(\sqrt{f^2+1} - f \right), \tag{2}$$

$$\varphi = \arcsin \frac{1}{\sqrt{2\left(f^2 - f\sqrt{f^2+1} + 1\right)}}, \tag{3}$$

where ω is the angular speed of the roller; x is the path of the seed along the roller mechanism; f is the coefficient of friction of the seeds along the material of the roller blade.

As can be seen from these equations, the speed of the movement of seeds along the blades of the turbine and the rate of their departure from the blades do not depend on the weight of the seed. In other words, seeds of different weights and sizes are ejected from the turbine at the same speed. A similar conclusion was independently reached based on the analysis of the equations of the relative movement of the seed along the roller mechanism. This suggests that it is possible to organize the flow of seeds along the blades of the roll into one thread, thus eliminating collisions between seeds in flight and reducing the incidence of defects in the sheller (Shcherbakov, 1992).

The principle of operation of the centrifugal dehuller allows for the possibility of incomplete husking of some seeds. In fact, the rate of ejection of seeds from the turbine and the force of their impact on the deck depend on the coefficient of friction, which decreases as the coefficient increases. This fundamental relationship is visible from equations (1) and (2). However, the coefficient of friction is a function of the condition of the seeds and, in particular, increases with their humidity. The strength of safflower seed coats is also a function of humidity, and this function has a maximum. Since the humidity of individual seeds varies, often significantly, due to differences in the

TABLE 1 Influence of humidity of safflower seeds on the efficiency of their peeling.

Humidity of seeds, %	Composition of grained seeds, % of number of seeds, that have been shelled				
	Whole seeds	Damaged seeds	Whole kernel	Damaged kernel	Cut
3.5	0	10	32.4	23.8	33.8
6.7	16	25	40.5	12.5	6.0
7.5	32	17	42.0	7.5	1.5
8.7	35	18	40.2	2.0	5.0

TABLE 2 Influence of safflower seed size on hulling efficiency.

Long fraction of seeds, *mm*	Composition of grained seeds, % of number of seeds, that have been shelled				
	Whole seed	Damaged seed	Whole kernel	Damaged kernel	Cut
Less than 5	34	40	21	2	3
From 5 to 7	23	34	31	5	6
More than 7	10	30	47	13	3

friction coefficients of the speed of their departure from the turbine and flight to the deck, they cannot be the same, and therefore they inevitably collide with each other. This weakens their impact on the deck and leads to the appearance of damage in the rushshank. The influence of humidity on the efficiency of safflower seed crushing is shown in Table 1. The data from Table 1 confirm the above-described ideas about the role of seed moisture in peeling efficiency and show the existence of an optimal moisture content of 7.5%–8.0%.

Since the weight of the individual seeds is different, the kinetic energy they develop in flight and the force of the impact on the deck are different. As a result, some seeds will remain undestroyed and some even the kernel will be shredded. This is supported by Table 2, which presents the results of 8.2% moisture peeling of safflower seeds on experimental equipment at 1000 rotations per minute.

As can be seen from this Table 2, as the size of the seeds, that is, their weight, increases, the content of the damaged kernel increases. At the same time, the contents of damaged and whole seeds are reduced, which corresponds to an increase in the force of the impact on the deck with an increase in the weight of individual seeds. The denominator of the right-hand side of equation (3) is directly proportional to the absolute velocity of the seed movement, i.e. the angle φ increases as it decreases, which further reduces the impact on the deck and can lead to the presence of husks and whole seeds in the equipment. This is the percentage of absolute speed reduction that results from an increase in the friction coefficient but not a decrease in the rotor speed (Larin, 2006). The condition of operation of any roller mechanism – the possibility of capturing the material in the husking zone. Particle capture is characterized by the α capture angle, which refers to the angle formed by the line connecting the centers of the rolls OO_1 with the line drawn from the center of the particle to the center of one of the rolls. A particle of material exerts pressure p on rolls at points A and A_1, directed at the normal to the surface of rolls and depending on the weight of the particle, the rate of its fall on rolls and some other factors. The reaction of rolls, for example, at

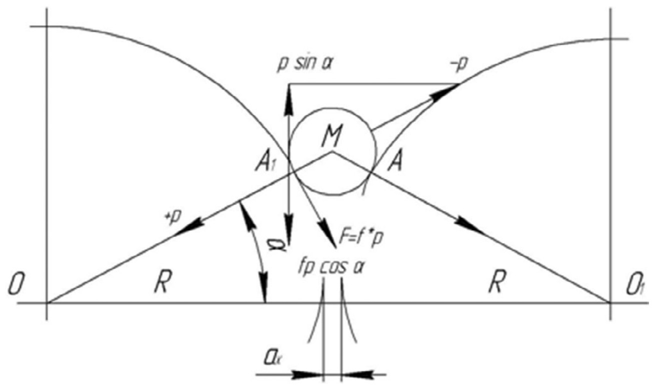

FIGURE 3 Safflower seed nip scheme with roll mechanism.

point A_1 is also equal p, but directed in the opposite direction. The two vertical components of these forces act on the particle differently: the constituent $p\sin\alpha$ tends to push out the particle, and the constituent $fp\cos\alpha$, where f is the coefficient of friction, to pull in. Since the particle has the shape of a ball, the condition of the particle passage into the roll nip is given:

$$2p\sin\alpha < 2fp\cos\alpha. \tag{4}$$

From this equation it can be got:

$$\frac{\sin\alpha}{\cos\alpha} < f \text{ or } \mathrm{tg}\,\alpha < \mathrm{tg}\varphi \text{ and } \alpha < \varphi. \tag{5}$$

So, for the particle to pass through the interval between the rolls, the angle of nip must be less than the friction angle. Hence, it is easy to determine the minimum diameter of rolls.

The angle of nip depends on the size of the particles, the diameter of the rolls and the distance between the rolls (Figure 3). With the

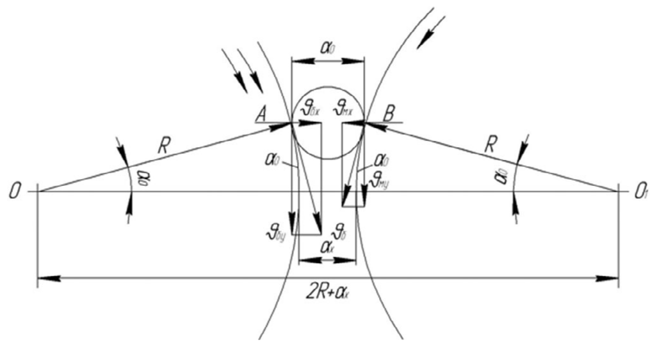

FIGURE 4 Distribution of the circumferential velocities of the roller mechanism along the axes of coordinates (to determination of the husking duration). α_0– initial value of the angle of nip α.

persistence of these characteristics, with the stable operation of the preparatory departments of the oil mills, the theoretical determination resulting from inequalities (5) is complicated by changes in the humidity and oil content of the seeds. Since the friction coefficient increases with the humidity of the material, in theory, the gripping conditions would have to improve, but in practice the material sticks onto the roll, which disrupts the normal husking. The high humidity of the particles also facilitates the extraction of oil from them during husking, which leads to a decrease in the friction coefficient and worsening of the gripping conditions. In practical conditions, the nip is complicated also because the roll nip does not receive individual particles, but their conglomerates, for example, when agglutination particles (Larin, 2006).

After capturing of the seed, the roll acts on it in a certain way for a certain period of time τ. The path of the center of gravity is equal to M:

$$L=\frac{2R+\alpha_{\kappa}}{2}tg\,\alpha \tag{6}$$

where a_k – the roll nip.

From Figure 4, which shows the velocity distribution of the slow and fast rotating roll along the x- and y-axis, it is possible to approximate the mean velocity of material movement in the husking area without taking into account the sliding of seeds along the roll surface and flute shape:

$$v_{av}=\frac{v_f+v_s}{2}=\frac{v_f+v_s}{2}cos\alpha, \tag{7}$$

where v_f and v_s are the circumferential velocities of fast- and slow-moving rolls.

By dividing equations (6) and (7), it can be obtained the duration of peeling:

$$\tau=\frac{2R+a_{\kappa}}{v_f+v_s}\cdot\frac{tg\,\alpha}{\cos\alpha} \tag{8}$$

If the rolls rotate at the same circumferential speed, $v_f=v_s=v$, then equation (8) will lead to:

$$\tau=\frac{2R+a_{\kappa}}{2v}\cdot\frac{tg\,\alpha}{\cos\alpha} \tag{9}$$

The larger the radius of the rollers and the smaller the circumference of the rollers, the longer the hulling time. As the angle of nip increases, the hulling duration increases rapidly as $tg\,\alpha$ increases and $\cos\alpha$ decreases. Equation (6)–(9) is true in the absence of elastic aftereffect of the seeds, that is, in the absence of elastic deformation of the seeds after passing through the line of the roll centres. The pressure on the material changes as it moves towards the roll center line. The pressure on the roll is given as an equation:

$$R_r=\frac{2}{3}PkRl \tag{10}$$

where $P=4.5\frac{\delta}{d}$ is the force of the crushing resistance; (δ is the relative compression of the particles, d is the particle size); k is the ratio of the material filling of the surface of the rolls; l is the length of the rolls. R_B power is applied to rolls at an angle of $\frac{3}{8}\alpha$.

The maximum pressure on the material is equal (assuming it is proportional to the compression value of the material):

$$P_{max}=\frac{4T}{Dl\sin\alpha} \tag{11}$$

where T is the force on the rolls; D is the diameter of the rolls.

Force on rolls equal to:

$$T=\frac{lD^2\alpha}{4}\sin\alpha(1-\cos\alpha), \tag{12}$$

where α is the proportionality ratio between the pressure and the compression value of the material.

The mean average velocity of the material in the husking area – equation (7) – allows to determine the theoretical performance of the roller pair. It is equal (in kg/h):

$$Q_{\mathrm{T}}=3.6\gamma l v_{av}a_{av}\varphi \tag{13}$$

where γ – volume weight of material before husking, g/cm^3; a_{av} – average clearance roll nip in the husking area in cm; φ – degree of filling of the volume of the husking area.

3.3 | Description of experimental centrifuge for primary purification of safflower oil

For effective primary purification of safflower oil, a prototype equipment for simultaneous filtration and sedimentation under the action of centrifugal force has been developed (Figure 5) (Kovalev, 2001).

The experimental centrifuge consists of the following main bodies: working cylinder, perforated filter rotor (Figure 6) and rotor

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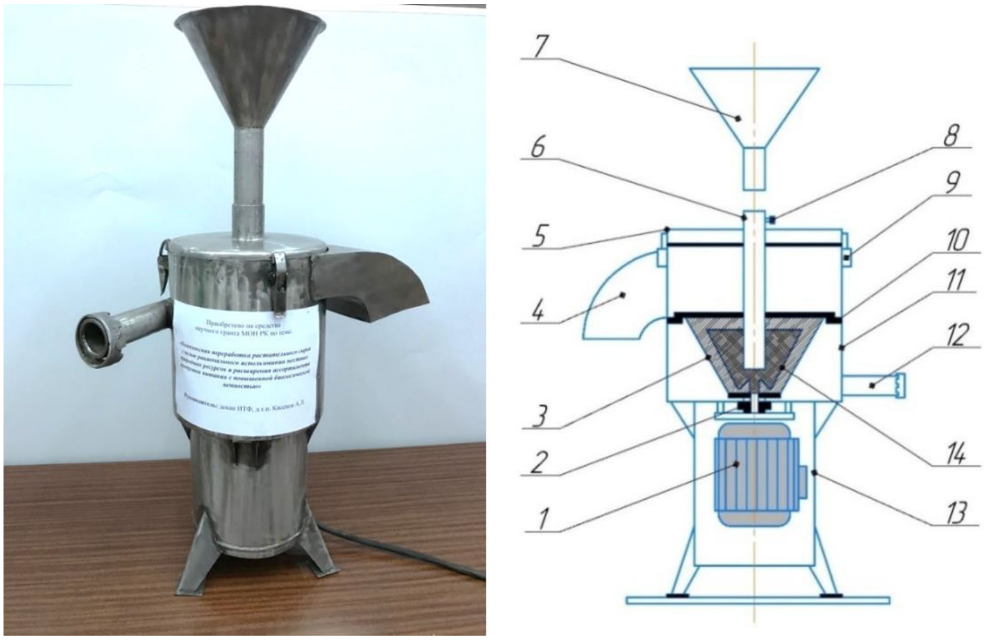

FIGURE 5 General form of centrifuge for primary purification of safflower oil. 1 – electric drive motor; 2 – coupling drive and seal; 3 – perforated filter rotor; 4 – tray output dehydrated fraction; 5 – cap centrifuge; 6 – charging adapter; 7 – filling hopper; 8 – bolt mounting hopper; 9 – locks of centrifuge; 10 – partition flange; 11 – centrifuge housing; 12 – intake connection for purified oil; 13 – protection electric motor cover; 14 – rotor sedimentation tank.

FIGURE 6 Perforated filter rotor.

sedimentation tank (Figure 7), partition flange, intake connection for purified oil, etc.

Safflower oil is supplied from the top, through the filling hopper. The funnel is attached to the lid of the centrifuge and is fixed with a bolt. The lid itself is mounted on the centrifuge body and is fastened with three locks. Under the action of centrifugal force safflower oil moves along the perforated surface of the rotor. Furthermore, the purified safflower oil penetrates through the perforation holes and flows into the lower part of the centrifuge tank and is discharged into the receiving tank through the fitting. The mechanical impurity moves along the surface of the rotor to the upper area and is removed through the tray. As a result of the installation of a perforated filter and slurry rotor in the centrifuge design, it can be provided a combination of two processes and an effective primary purification of the pressed oil.

FIGURE 7 Rotor sedimentation tank.

3.4 | Centrifuge engineering design calculation methodology

Calculation engineering schemes of equipment are provided based on calculations reflected in numerous works (Amirkhanov et al., 2019; Brazhnikova, 1973; Shamenov & Zhienbaeva, 2004; Shkoropad & Veksler, 1975; Tombaev, 1962). In the main, when choosing the designs of equipment considered their own possibilities of primary purification of safflower oil on the equipment and mechanisms, taking into account the needs of the development of production, in this regard, using the results of the study, offer engineering calculations of new centrifuge equipment (Medvedkov et al., 2021). Algorithm of calculation and programming, compiled under engineering methods of calculation of filters and sedimentation centrifuges in WINDOWS Math Soft Inc. MathCad 2000 (9.0) Rus and MATLAB 9.9 R2020b programs conducted through companies (Systems for scientific work, 2020; MATLAB program, 2020). Engineering calculation consists of 3 main units: constant dimensions for all centrifuge paths; centrifuge operation calculation; matrix of calculation results. The first unit of engineering records is all constant values used in the centrifuge calculation. There are ρ – suspension density, kg/m^3; μ – viscosity effectiveness of suspension; D – rotor diameter, m; H – rotor height, m; $M\delta$ – rotary mass, kg. Figure 8 shows the permanent size determination unit for all centrifuge paths. Other unit parameters are given depending on the operating conditions of the centrifuge to be designed.

The second engineering unit consists of a unit describing the operation of the centrifuge according to Figure 9.

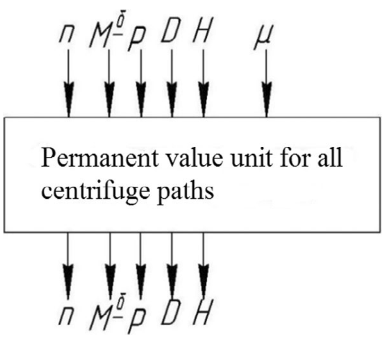

FIGURE 8 Permanent value unit for all centrifuge paths.

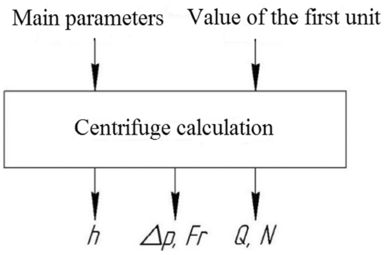

FIGURE 9 Centrifuge calculation unit.

There are Fr – separation factor; h – sediment layer thickness, mm; Q – sediment capacity, kg/sag; μ – product viscosity, Pa/s; N – energy consumption, kW; ΔP – pressure difference on the surface of the rotor, Pa.

3.5 | Methods for calculating the separation factors and sediment layer thickness in each rotor area

The separation coefficient shows how many times the acceleration of the centrifuge field of the centrifuge is greater than the acceleration of the gravitational field. The separation coefficient shall be determined as follows:

$$Fr = \frac{\omega^2 r}{g} = \frac{\pi^2 n_r^2}{15g} r, \tag{14}$$

where ω – angular speed, rad/s; n_r – rotor speed, rpm; r – inside radius of the rotor, m; g – acceleration of the gravitational field, m/s^2.

If the whole process takes time τ and consider the centrifuge according to Figure 8, it can be assumed that the rotor length will be L, and take into account the influence of centrifugal forces and Coriolis force G_c and G_k (Figure 10).

G_c – centrifugal force, N:

$$G_c = -m_1\omega^2\sqrt{\left(r_2^2\cos^2\Psi - r_1^2\cos^2\alpha\right)}. \tag{15}$$

G_k – Cariolis force, N:

$$G_k = 2m_1\lfloor v\cdot\omega\rfloor = 2m_1 v\omega\sin(v\cdot\omega). \tag{16}$$

where $v = \frac{\sin\alpha\sin\psi}{\sin(\alpha+\psi)}\frac{r_i}{\tau}$ – increased speed in centrifuge, m/s.

If consider these forces on the basis of Newton's second law:

$$m_1 a_1 = G_c + G_k, \tag{17}$$

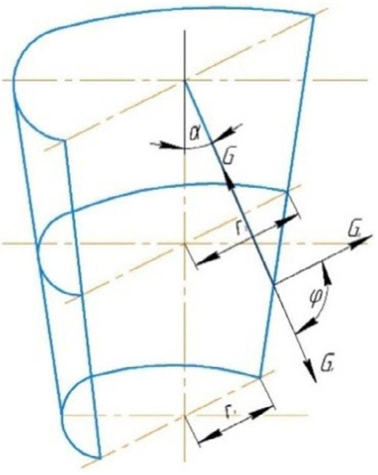

FIGURE 10 Force projection.

Projection of forces on material direction:

$$G = m_1(g - a_1). \tag{18}$$

Find the acceleration if the straight-trough track $L = \frac{a\tau^2}{2}$ corresponds to the rotor length, $a_1 = \frac{2L}{\tau^2}$ In this case, under the influence of centrifugal force, particles replace places, as the centrifugal force is greater than gravity, in this case mg can be ignored:

$$m\overrightarrow{a_2} = \overrightarrow{G_k} + \vec{G}_c, ma_2 = u\omega^2\sqrt{\left(r_2^2 cos^2\Psi - r_1^2 cos^2\alpha\right) - G_k}, \tag{19}$$

where $u = \frac{n_1}{n_2}$ – rotor rotation ratio n_1 и n_2 products; time $t_0 \to 0$; so $a_1 = 0$; $a_2 = 0$.

If $mg = G_1$, $ma_c = G_2$, where the dividing factor can be obtained as follows:

$$F_r = \frac{a_c}{g}. \tag{20}$$

If insert this equality into equation (3):

$$mgFr - G_{c1}Fr = ma_2, \tag{21}$$

So:

$$a_2 = gFr - \frac{G_{c1}}{m}Fr = nFr\left(g - \frac{G_{c1}}{m}\right). \tag{22}$$

Solving this equation, it can be got the following equality:

$$Frmg - FrG_{c1} = nma_1Fr. \tag{23}$$

This equation characterizes the movement of particles within the rotor during centrifugation. Taking into account these efforts, it can be determined the disconnection factor by means of the gear ratios of a given rotor and the product rotation number:

$$F_r = u_{a_2}^{a_1}. \tag{24}$$

$$K_{\mathrm{H}1} = \frac{\pi D cos\alpha_{\mathrm{op.}}}{2} \cdot h \cdot \frac{(a+b)}{2} \cdot F_d \cdot \psi, \tag{25}$$

If set the formula of rotor geometry parameters and calculate simultaneously:

$$Fr = u\frac{2L}{r_i} \tag{26}$$

Looking at Figures 10 and 11 it can be found the thickness of the sediment layer h in each area.

If you consider the area in the rotor as three parts, the thickness of the sediment layer in each part will be different. Since, if $P = $ const,

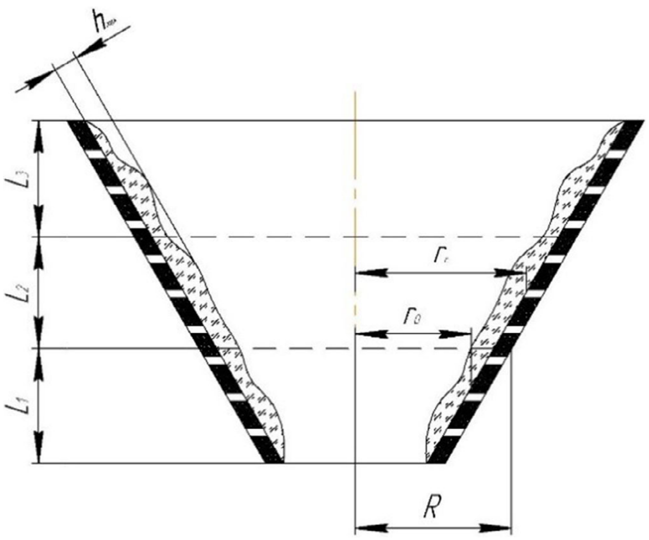

FIGURE 11 Centrifuge rotor separation areas depending on the separation process.

bulk sludge losses pass through the surface of the filter layer in time V, t, the filtration coefficient $F = \frac{V}{\varpi}$ or the permeability coefficient in each zone changes with the change of the inside radius of the layer. Then $k_n \le 0.75$. 1 area:

$$h_1 = \frac{kr_1}{ln\frac{R}{r_1}}. \tag{27}$$

2 area:

$$h_2 = \frac{kr_2}{ln\frac{R}{r_2}}cos(2\alpha - \psi). \tag{28}$$

3 area:

$$h_2 = \frac{kr_3}{ln\frac{R}{r_3}}cos2\alpha sin\psi. \tag{29}$$

3.6 | Methods for calculating the centrifuge pressure differential and the draught capacity in each rotor area

The above-mentioned values can be used to calculate the main parameters of the research work. The differential pressure on the lateral surface of the rotor is linearly dependent on the sediment layer density. It is determined by the following equation:

$$\Delta p = \frac{\mu \cdot \omega \cdot h_i}{\pi^2 D^2}\left(ln\frac{r_i}{R}\right)r_i cos\alpha(1 - sin\psi), \tag{30}$$

where D is the diameter of the rotor, m; R is radius of the centrifuge spindle, m; α is the angles of the reversible and indirect lines in the direction of centrifugal force, rad; υ_α is the linear indirect velocity, m/s; r is the distance from the particle to the rotor axis, m.

Centrifuge performance is its main characteristic. The performance of the centrifuge oil is produced through filtration and sedimentation processes. Thus, the weight of the oil ratio is determined by the difference between the weight loss of the original suspension, the sum of the weight loss of fugue obtained during the sedimentation and the filtration leachates obtained during the filtration process, and determine the surface flow as a Newtonian liquid, kg/s:

$$Q = Q_c - \left(Q_{fug.} + Q_{fil.}\right). \tag{31}$$

The weight output obtained from the suspension shall be determined as follows:

$$Q_c = 3.5\frac{D^2 L(\rho_l - \rho_s)}{\mu} b^2 n^2. \tag{32}$$

And the weight losses of centrates produced during deposition and filtrates produced during the filtration process are determined by dividing them into each area of the rotor. For 1 area:

$$Q_1 = h_1 \frac{F(\rho_l - \rho_s)\omega\sqrt{Fr\frac{(r_1+r_2)}{r_1}\ln\frac{r_i}{R}}}{0.25k}. \tag{33}$$

For 2 area:

$$Q_2 = h_2 \frac{F(\rho_l - \rho_s)\omega\sqrt{Fr\frac{(r_2+(r_3-r_2))}{r_2}\ln\frac{r_i}{R}}}{0.75k}. \tag{34}$$

For 3 area:

$$Q_3 = h_3 \frac{F(\rho_l - \rho_s)\omega\sqrt{Fr\frac{r_3+(r_3-r_2-r_1)}{r_3}\ln\frac{r_i}{R}}}{k}. \tag{35}$$

where b is the height of the areas in the rotor, m; F is the surface of the sediment in the rotor, m^2; ρ_l is the density of the liquid phase, kg/m^3; ρ_s is the density of the suspension, kg/m^3; μ is the dynamic viscosity, Pa/s.

In this way, get the weight output of centrates obtained during the deposition process $Q_{cent.} = Q_3$ and the weight output of the filters obtained during the filtration process $Q_{fil.} = Q_1 + Q_2$. On the basis of the obtained equations (29)–(35) it can be seen that the performance of the sediment by engineering calculation depends on the performance of the centrifuge and the various separation factors according to Figure 12.

3.7 | Methods for calculating the centrifuge power consumption

Calculate the power consumption using the following consumption formulas. Rotor power:

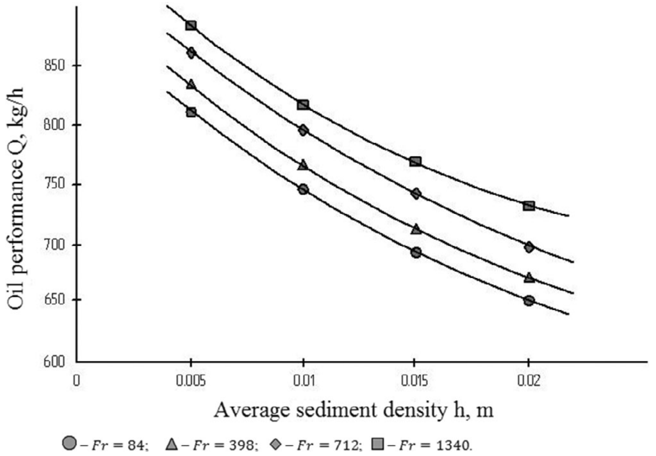

FIGURE 12 Dependence of oil performance by engineering calculation on average sediment density and various separation factors.

$$N_1 = \frac{\omega^2 M}{2}\eta, \tag{36}$$

where ω – rotor speed, rad/s; M – rotor mass, kg; η – coefficient of efficiency.

Friction energy:

$$N_2 = 2.94\beta R^2 \omega^2 (\rho_l - \rho_s), \tag{37}$$

where β – coefficient of resistance.

Installed power consumed during shutdown:

$$N_3 = \frac{\Delta p F \omega}{F_r}\sqrt{\frac{h}{r_i}}. \tag{38}$$

From the equations (36)–(38) determine full power, W:

$$N = N_1 + N_2 + N_3. \tag{39}$$

On the basis of the obtained equation (38), shall demonstrate the dependence of the power by engineering calculation on the average sediment thickness and various partitioning factors graphically in accordance with Figure 13.

3.8 | Methods for calculating dewatering of sediment

The residual fat in the sediment is determined according to the centrifuge speed, layer thickness and particle distance to the rotor berth axis and the trip factor. The filling ratio indicates the position of the rotor layer $k_n \le 0.75$ and $d' = \left(\frac{k_n S''_{n_1}}{N_{n_1}}\right)^{1/2}$ is the diameter of the filled rotor, hence the distance between the layer thickness and the rotor axis can be determined:

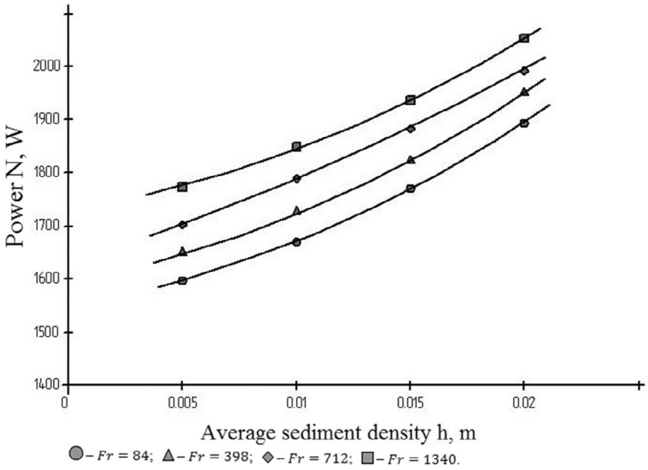

FIGURE 13 Ratio of engineering power to average sediment thickness and various separation factors.

$$t_{cp_1} = \frac{\pi \cdot (D_1 + h_{n_1})}{Z_1}. \tag{40}$$

Inside sediment radiuses in the first and second areas shall be calculated as follows, m:

$$r_2 = \frac{\pi(H - 2H_i) - z_2 b_{32}}{2(z - \pi)}, \quad r_1 = \frac{\pi(H - 2H_i) - z_2 b_{32}}{2(z + \pi)}, \tag{41}$$

where z_i – number of gaps in the area in question; H – rotor height, m; H_i – distance from each cross section of the sediment layer to the rotor base, m; b – height of zones in rotor, m.

In this case, based on the above, will determine the residual fat of the sediment obtained by filtering and sedimentation as follows:

$$\varphi = \frac{2\varphi_1 \varphi_2}{\varphi_1 + \varphi_2}. \tag{42}$$

Here is the residual fat in the filtration process:

$$\varphi_1 = 2\varphi_0 \sqrt{\frac{b}{h_1} \frac{\left(1 - \frac{r_1}{t_{ch}}\right)}{1 - \frac{\rho_l}{\rho_s}}}. \tag{43}$$

Residual fat of sedimentation:

$$\varphi_2 = 2\varphi_0 \sqrt{\frac{b}{h_2} \frac{\left(1 - \frac{r_2}{t_{ch}} sin\alpha\right)}{1 - \frac{\rho_l}{\rho_s}}}. \tag{44}$$

where φ_0 – raw material fatness, %, φ_0 to calculate the specific mass of the solid phase of the suspension $x = 0.139$, filter constant $K = 278 \times 10^{-4}$:

$$\varphi_0 = 0.139 + 278 \times 10^{-4} \omega - \frac{b}{z}. \tag{45}$$

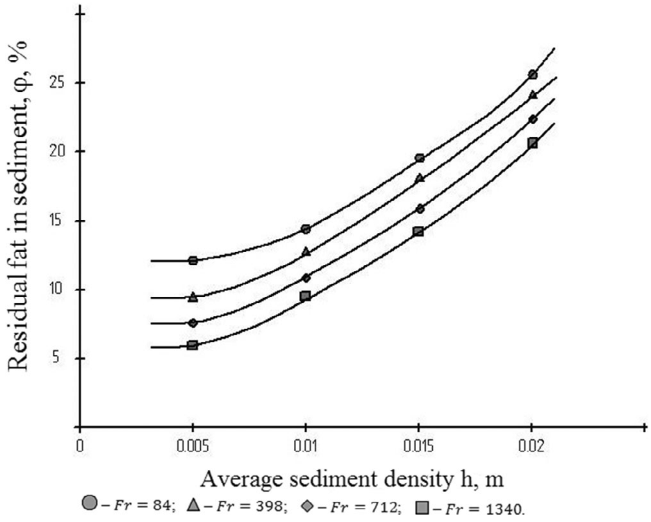

FIGURE 14 The dependence of residual fatness in the engineering calculation of the mean sediment thickness and various separation factors.

Based on the equations (42)–(44) obtained, Figure 10 illustrates the dependence of the residual fat of the sediment on the engineering calculation of the average thickness of the sediment and various partitioning factors. Furthermore, Figures 12–14 demonstrate that the compatibility of engineering calculations for disabling liquid heterogeneous systems, qualitatively and quantitatively, through mixed processes that are broken down into separation zones, depending on the centrifuge deposition and filtration processes, coincides with the results of mathematical modeling and experimental studies.

The results of engineering calculations show that the deviation between theoretical and practical studies was determined in the range of 3.8–4.3.

4 | CONCLUSIONS

In conclusion, this study successfully developed a small-scale processing line for safflower oil production, which is essential for improving the consumption pattern of food products. The newly developed processing line combines husking, compressing, filtration, and sedimentation to ensure primary purification of plant oils and the removal of mechanical impurities. The research also highlighted the importance of primary purification of plant oils and its impact on the quality of the final product. The results of this study have significant practical implications for small enterprises in the cereal-processing industry, particularly in Kazakhstan, where safflower oil has gained increasing popularity.

The scientific value of this work lies in the successful development of a new processing line, which can improve the production of high-quality safflower oil with great potential for the industry. This study provides valuable insights into the primary purification of plant oils and highlights the importance of efficient oil processing methods for maintaining the biological value of plant oils.

In terms of future research, further studies could focus on optimizing the processing line to increase its efficiency and reduce costs. Additionally, the research could explore the potential of safflower oil in other industries, such as cosmetics and pharmaceuticals. Overall, the objectives of the conducted research have been achieved, and the results of this study have significant practical and scientific value.

AUTHOR CONTRIBUTIONS

Maigul Mursalykova: Methodology; writing – original draft. **Bauyrzhan Iskakov**: Writing – review and editing; project administration. **Mukhtarbek Kakimov**: Validation and conceptualization. **Gulmira Zhumadilova**: Visualization and investigation. **Assem Shulenova**: Supervision. All authors read and approved the final manuscript.

CONFLICT OF INTEREST STATEMENT

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

Ethics Committee approval is not required for this kind of study in the country where the study was conducted.

ORCID

Maigul Mursalykova https://orcid.org/0000-0001-5431-9306

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