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Fibre extraction from oilseed flax straw for various technical applications

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Abstract
Cultivated primarily for seeds and oil, oilseed flax can be evaluated as a source of natural fibre that can be extracted from straw. However, due to the lack of comprehensive processing of the stem mass, they remain in the fields and are burned. The aim of this research is to study the possibility of obtaining fibre from oilseed flax straw by mechanical processing and to study the technological properties and suitability of the resulting fibre for technical use. In the course of the work, the structural and technological properties of straw samples of 4 varieties of oilseed flax were studied. The chemical composition was studied and fibre samples were obtained according to the scheme consisting of crushing, scutching, milling and shaking machine. Optimal modes of fibre extraction were established by developing a mathematical model of the process. The results of the work show that the fibre of oilseed flax is comparable to textile flax in terms of physical and mechanical parameters, which makes it suitable for technical use.

Keywords: oilseed flax straw, oilseed flax fibre, fibre yield, cellulose

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INTRODUCTION

Oilseed flax is a highly profitable annually renewable industrial crop. According to the Food and Agriculture Organization (FAO), oilseed flax crops in the world are very significant and amount to more than 3 million hectares, the seed harvest reaches 2.6-3.0 million tons. The largest oilseed flax crops are in Canada, Kazakhstan, Russia, China, the USA, and Argentina. In the world, the practice of burning oilseed flax straw is a thing of the past and it is considered not only as a crop for obtaining seeds, but also as a cost-effective additional textile raw materials. According to world experience, industrial use of oilseed flax straw is used to produce innovative products of various functional applications. In addition, these products are environmentally friendly and meet modern consumer requirements of the population (Golovenko *et al.,* 2017; Novikov *et al.,* 2018).

From natural fibres, flax is considered one of the most durable (Bos *et al.,* 2002). In appearance, the stem of oilseed flax is a strongly elongated cone, expanded at the base and narrowed at the top. The stem of oilseed flax consists of a woody and fibre part. Strands of coarse fibre are separated from the stem by mechanical decortication (Mussig and Martens, 2003). The wood part of the shives can be used as a fuel for generating heat and electricity, fertilizing crops, and producing extruded and molded wood-polymer composites (Gamon *et al.,* 2013). There is a certain practical interest in obtaining organic acids from cellulose-containing raw materials: acetic, oil, etc. In the literature sources there is data on the possibility of using shives to produce furfural, which is important for the manufacture of plastics. It is possible to obtain activated charcoal from shives, since the morphological structure of the original plant products plays an important role in such sorbents. Fibre and oilseed flax shives are the most suitable for the production of cellulose and semi-cellulose used in the production of paper and cardboard. The analysis of foreign studies on the processing of oilseed flax production wastes allows to conclude that the production of fibre from oilseed flax straw and its use as a valuable raw material for the production of non-woven and heat-insulating materials, polymer composites, cellulose and cotton wool is currently an important and promising direction (Tikhosova, 2013).

Currently, the issue of using oilseed flax straw is widely dealt with in many countries. According to the

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Ministry of Agriculture of the Republic of Kazakhstan (MA RK) for the last 10 years (2009 – 2019), in comparison with several other industrial crops, oilseed flax seeds increased significantly - from 9.8 thousand hectares to 1 289 thousand hectares. In turn, the flax stems contain in its composition from 20 to 24% of a fibrous material. According to statistics on the average yield of straw – 2 t/ha, in 2019, 2.6 million tons of oilseed flax straw were obtained from the sown areas. At the same time, due to the lack of a comprehensive technology for processing the stem mass of oilseed flax in Kazakhstan in 2019, 520 thousand tons of fibre were lost (with an average yield of 20%), which is burned in the fields, causing huge damage to the environment (Shaimerdenov *et al.,* 2019). If the seeds of oilseed flax are well valued, then the straw has not found proper use. It is milled at the same time during harvesting of seeds. This mainly explains why technical fibres from oilseed flax are not available on the market, despite the fact that the mechanical properties of individual oilseed flax fibres are described in comparatively many studies (Rennebaum *et al.,* 2002; Tomljenovic and Erceg, 2016; Pillin *et al.,* 2011).

Harvesting oilseed flax does not allow the straw to be processed using the same methods as for textile flax. The stems are mowed down and directly absorbed by the harvesting machine, which separates the seeds from the straws using integrated threshers. Therefore, straws are subjected to mechanical loads during the threshing phase. At the end of the threshing phase, straws regularly fall out of the combine and form a roll of randomly oriented stems. Then the straws are left in the field for retting. The most important and energy-intensive stage in the processing of oilseed flax straw is retting, which leads to the separation or loosening of fibrous inner barks from the wood part (Foulk *et al.,* 2001). When straw is not sufficiently retted, coarse fibres of poor quality are formed with pointed and cuticular fragments, and when excessive retting occurs, the maximum destruction of cellulose occurs, which leads to excessive thinning of the fibre (Adamsen *et al.,* 2002; Gusovius, H. J. *et al.,* 2019). There are two traditional methods of retting, water and dew. Despite the fact that the quality of the fibre in the retting is much higher than in newer methods, this practice has been largely discontinued due to its high cost and environmental pollution resulting from the fermentation of plant raw materials. There are also methods for collecting straw after wintering, taking into account climatic conditions (Hoffmann et al., 2013). After that, the oilseed flax stems are machined to extract the fibre (Ouagnea *et al.,* 2017).

The aim of this research is to study the influence of the parameters of mechanical processing on the yield of fibres from oilseed flax straw and to study the physical, chemical and technological properties of the resulting fibre.

METHODS OF RESEARCH

Materials

The research used samples of straw of 4 varieties of oilseed flax: Kostanaysky yantarny, Lirina, Kostanaysky 11, Kazar, grown in the Northern part of Kazakhstan. The average height of plants is from 60 to 68 cm: Kostanaysky yantarny 60-65 cm, Lirina 58-78 cm, Kostanaysky 11 60-65 cm, Kazar 65-68 cm. Since weather conditions are not suitable for natural retting of straw, a batch of straw was left in the fields for the winter under snow, then in the spring it was collected for further mechanical processing.

Determination of moisture content

Since the mechanical behavior of lignocellulose fibres of oilseed flax varies depending on their moisture (Placet *et al.,* 2012), it is important to determine the amount of water absorbed. Thus, it is possible to study the influence of straw moisture on the physical, mechanical and technological properties of the fibre. The moisture content was determined in accordance with ISO 665:2000.

Structural analysis of stems

To study the structural features of the fibre, the stems that are most characteristic of each variety were selected. Since the determination of anatomical characteristics was carried out along the length of the stem, segments 3-4 cm long were cut from the butt, middle and apex parts of the stems. Then the segments were placed in trachea with a mixture of glycerol, distilled water and alcohol in equal proportions and kept for 2-3 days. Sections of the stem for microscopic studies were performed using a blade in the middle of one of the internodes. Then the sections were treated with aniline sulphate, and when these chemicals are processed, the lignified middle plates turn yellow. The structural features of the stems were studied using a microscope (Gibaud *et al.,* 2015).

Determination of the chemical composition of stems

Determination of cellulose content.

To determine the cellulose content, about 1 g of stems was used, taken with an accuracy of 0.0002 g, placed in a cone flask with a capacity of 200-250 ml, 25 ml of a mixture consisting of 1 volume of concentrated nitric acid (density 1.4) and 4 volumes of ethyl alcohol and boiled for 1 hour in a flask with a backflow condenser in a water bath. After boiling, allow the stems to settle and carefully drain the liquid through a glass filter, which is pre-dried to a constant mass and weighed. The stems that have got on the filter are washed off in a flask of 25 ml of a fresh mixture of alcohol with nitric acid and heated again in a water bath in a flask with a backflow condenser for 1 hour. This processing is carried out 3-4 times (Devyatlovskaya *et al.,* 2011).

Determination of lignin content

To determine the lignin content, the studied plant tissue is milled, sifted, a fraction of the stems of 0.2-2 mm in size is selected and dried to an air-dry state. Before analysis can determine the moisture content of the sample. About 3 g of air-dry stems are placed in an extraction apparatus and resins, fats and other substances are extracted with an alcohol-benzene mixture. Calculate the content of extractives in the analyzed sample. Then take about 1 g of deresined completely dry sample, quantitatively transfer it to a porcelain cup, add 15 ml of 72 % sulfuric acid, mix thoroughly and leave to stand for 3 hours at room temperature, stirring periodically. After 3 hours, the mixture is quantitatively transferred using 200 ml of water to a cone flask with a capacity of 500 ml, the flask is closed with a stopper, in which the backflow condenser is inserted, and placed on the included electric stove. The contents of the flask are boiled for 1 hour and left to stand for 1 day, so that lignin particles become larger and settle to the bottom of the flask. The next day, the lignin precipitate from the flask is quantitatively transferred to a glass filter, filtered using a vacuum, washed with hot water until a negative reaction to the SO_4^{2-} ion - by methyl orange or barium chloride $BaCl_2$ and dried in a drying box at 105°C until the moisture is completely removed (Obolenskaya, 1993).

Determination of extractable substances content

Determination of the content of extracted substances was carried out on Soxhlet device. A suspension of air-dry milled stems weighing about 2-5 g is placed in a cartridge rolled from filter paper. The cartridge with the stems is placed in the extraction nozzle, and the level of stems in the cartridge should be 1-1.5 cm below the level of the siphon tube. 150 cm^3 of diethyl ether is poured into the flask. Collect the device and put it in a water bath. The temperature of the bath is adjusted depending on the solvent used. Extraction is continued for 6-8 hours at a vigorous boiling of the solvent (draining through a siphon tube should occur approximately every 10 minutes). Then the device is removed from the bath, disconnect the nozzle from the flask and the refrigerator. The solution is poured into a flask dried to a constant mass, and the solvent is distilled in a water bath through a direct condenser. All parts of the solvent distillation unit must be connected by sanding strips. The flask with the resin is dried in a drying box at a temperature of (103 ±2)°C to a constant mass and weighed.

Method for determining substances that are soluble in hot water. Hot water in addition to substances extracted by cold water, extracts water-soluble pectin substances and polysaccharides (starch, arabinogalactan). A suspension of air-dry sawdust weighing about 2 g is placed in a cone flask with a capacity of 250 cm^3 and filled with a measuring cylinder of 100 cm^3 of distilled water. A backflow condenser is attached to the flask and placed in a boiling water bath, with the water level in the bath being slightly higher than the water level in the flask. During the extraction process, a constant level of water in the bath must be maintained by adding boiling water. Extraction is carried out for 3 hours. Then the sawdust is filtered on a glass porous filter dried to a constant mass with suction, washing the sawdust from the flask onto the filter with hot distilled water. The filter with sawdust is dried to a constant mass in a drying box at a temperature of (103±2)°C and weighed. The mass fraction of substances soluble in hot water, as a percentage in relation to completely dry wood, is calculated by reducing the mass of wood according to the above formula. When determining the amount of water-soluble substances from the dry residue, a mixture of sawdust and water is filtered through a Buchner funnel with a paper filter. The filtrate and the first portion of the wash water are transferred to a 250 cm^3 volumetric flask, the volume of the solution is brought to the mark with distilled water and filtered through a cone-shaped glass funnel with a paper filter. A sample of 50 or 100 cm^3 is taken from the filtrate with a pipette, placed in a porcelain evaporation cup dried to a constant mass, and evaporated in a water bath to dry. The cup with the dry residue is dried in a drying box at a temperature of (103 ±2)°C to a constant mass and weighed (Obolenskaya *et al.,* 1991).

Determination of ash content

An empty porcelain crucible with a lid is calcined in a muffle furnace at a standard temperature (575±25)°C or other set temperature to a constant mass. In the crucible, place a suspension of stems weighing 2-3 g. Stems should occupy no more than half the volume of the crucible. Carefully incinerated sample stems on an electric plate (fume hood) or on the edge of the muffle furnace. If the crucible does not contain the entire suspension, then it is made in parts, carefully adding a new portion after the end of the previous one. In case of ash contamination, the sample must not be ignited to avoid loss of ash. Then, the crucible with ash was calcined in a muffle furnace at a predetermined temperature for 3-4 h. If the ash has a dark color, gently moisten with a few drops of 3% solution H_2O_2, evaporated liquid (putting the crucible on the furnace) and again calcined for about 1 h. Remove the crucible from muffle furnace with tongs, close lid and allow to cool a little, by placing on a fireproof base (1-2 min), and then transferred into a desiccator. After cooling in the exicator (30-40 min), the crucible with ash is weighed and calcined for 1 hour until a constant mass is reached (Obolenskaya *et al.,* 1991).

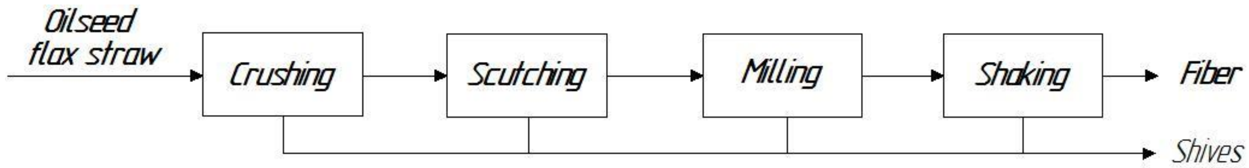

Fig. 1. Scheme of the process of extracting fibre from oilseed flax straw

Research of technological properties of fibre

Determination of the mass fraction of fibre and shives

Determination of the mass fraction of fibre and shives is carried out according to GOST R 53484-2009 “Flax scutched. Specifications”. From each sample of straw varieties, 100 g of the sample was taken for testing. Manual separation of fibres and shives was performed in the laboratory. After receiving the mass of separated shives and fibres, for the accuracy of the results, the fractions were dried in a drying box at a temperature (105±3)°C to a constant mass, then the fractions were weighed. The results were processed by the calculation method according to the methodology.

Determination of linear density of fibre

Determination of the linear density is carried out in accordance with GOST 10213.1-2002 “Staple fibre and chemical bundles. Methods for determination of linear density”. From laboratory samples of fibres, select the basic sample of weight not less than 0.2 g. Sample of the staple fibres by hand loosen on the board-stacker and prepared a strand of staple fibres, each pulling gently staple fibre and superimposing them on each other parallel to the axis of staple fibres. In this case, the staple fibres at one end of the strand must be on the same straight line. In the process of forming a strand of staple fibres, it is slightly smoothed and the uncompressed staple fibres are removed. Strand of staple fibres is clamped on the flat end side and pulled until the crimp is completely eliminated, the straightened section of the staple fibre strand is clamped with the lower plate of the cutter, cut out, put between a pair of slides and count the number of fibres, then weigh. Then, according to the formula, the linear density is calculated. The intermediate and final value of the actual linear density is calculated with the accuracy specified in GOST 10878.

Determination of the fibre breaking load

To determine the breaking load, 10 samples of 15 and 5 cm long, consisting of 40 fibres each, are prepared. During the day, the samples are kept in standard laboratory conditions. Then they are subjected to a break on Shopper pendulum type breaking machine with a distance between the clips of 100 and 5 mm respectively.

Determination of fibre defects

Fibre defects are determined as the ratio of the average breaking load of five-centimeter samples to the average breaking load of fifteen-centimeter samples.

Extraction of fibre from oilseed flax straw

To extract the fibre from the oilseed flax straw, a line consisting of a crushing, scutching, milling and shaking machine was used. The fibre extraction scheme is shown in **Fig. 1**.

The crushing machine passes a batch of straw through fluted rollers, thus destroying the fragile wood, but preserving the elastic fibre. At the entrance, the feed is provided by a pair of rollers, one of which is smooth and the other is fluted. The speed of passage of raw materials through crushing rollers adjustable from 10 to 50 m/min. The scutching machine repeatedly hits the stems with the blades of beater drums, thereby cleansing the fibre from shives and other impurities. In the disintegrator, the structure of the stems is destroyed, the wood is crushed and partially separated from the fibrous part. The speed of the working body of the disintegrator is from 700 to 1100 rpm. The shaking machine processes the waste of scutching, removes the bulk shives from the flax fibre, and also gives the fibre a marketable appearance. The number of swings of the rollers of the shaking field from 125 to 225 sw/min.

Optimization of the fibre extraction process

To obtain the mathematical model of technological process of extracting fibre from oilseed flax straw, which is a regression equation used rotatable plan of the second order (Box plan) when the number of factors K=3, the number of experiments plan 20, the number of experiments at the zero point was 6 and the number of coefficients is 10. To optimize the process of extracting fibre from oilseed flax straw, the following factors are established: the speed of the material passing through the crushing rolls (v, m/min), the speed of rotation of the disintegrator working body (n, min^{-1}), the number of swings of the shaking field rollers (*c*, sw/min), which affect the optimization criteria – the fibre yield (ŋ, %).

Next, we coded the intervals and levels of variation of input parameters, which are presented in **Table 1**. The planning matrix is shown in **Table 2**.

Table 3 shows the values of confidence intervals for optimizing the process of obtaining fibre from oilseed flax straw.

The coefficient of the regression equation is significant if its absolute value is greater than the

Table 1. Coding of intervals and levels of variation of input factors

Factors		Variation levels					Variation intervals
Natural	Coded	-1,68	-1	0	+1	+1,68	
v, m/min	x_1	10	20	30	40	50	10
n, min^{-1}	x_2	700	800	900	1000	1100	100
c, sw/min	x_3	125	150	175	200	225	25

Table 2. Matrix of rotatable planning of experimental studies of the technological process of obtaining fibre from oilseed flax straw

Coded values			Natural values			Experimental values
x_1	x_2	x_3	v, m/min	*n*, min^{-1}	*c*, sw/min	η, %
-	-	-	20	800	150	15,8
-	-	+	20	800	200	15,9
-	+	-	20	1000	150	16,1
-	+	+	20	1000	200	16,2
+	-	-	40	800	150	15,4
+	-	+	40	800	200	15,5
+	+	-	40	1000	150	16,5
+	+	+	40	1000	200	18,1
-1,68	0	0	10	900	175	18,2
1,68	0	0	40	900	175	18,3
0	-1,68	0	30	700	175	18,4
0	1,68	0	30	1000	175	18,5
0	0	-1,68	30	900	125	18,6
0	0	1,68	30	900	225	18,7
0	0	0	30	900	175	17,1

Table 3. Value of confidence intervals of the optimization criterion

The process of obtaining fibre from oilseed flax straw		Input parameter	Confidence intervals			
			Δb_0	Δb_i	Δb_{ii}	Δb_{ij}
Fibre yield	η, %	*y*	±0,70	±0,46	±0,45	±0,60

confidence interval ($bi>\Delta bi$). Otherwise, it is considered insignificant and can be excluded from further consideration of the mathematical model.

Comparing the values of confidence intervals with the corresponding regression coefficients, it can be concluded that the interaction effects of input factors are insignificant, and they can be ignored.

Next, searched for the optimal response functions with the highest possible accuracy (solving a compromise problem), while taking into account insignificant coefficients for constructing a mathematical model that will represent a regression equation:

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

The adequacy of the obtained mathematical regression models was evaluated using the Fischer criterion F_P.

RESEARCH RESULTS AND DISCUSSION

Structural analysis of stems

The choice of a particular straw characteristic for evaluation should be based on knowledge of the relationship of this characteristic to the quantity and quality of the fibre contained in the stems. The technological value of raw materials is determined not only by the total amount of fibrous substances contained in it, but also by the possibility of separating them from the stems in the form of a more valuable long fibre. The anatomical structure of oilseed flax stems was studied. In the process of primary processing of fibre crops, the fibrous layer is isolated from the stems in the form of technical fibre. Flax stems, which have a fibrous layer composed of tightly arranged and identical in size strands, and the strands contain uniform in diameter elementary fibres with a minimum internal cavity, are evaluated as the best in terms of spinning quality. Preferred strands are considered elongated-oval (tangent) shape, since such a fibre is better crushed during processing. Special attention was paid to the study of the main indicators of anatomical structure along the length of the stem presented in **Figs. 2-4**. The number of fibrous substances in the flax stalk depends on the number of strands on the cut and elementary fibres in the strand. One of the main indicators is the average size of the strands along the length of the stems of oilseed flax.

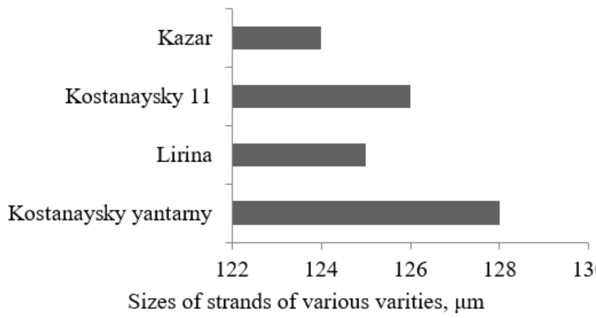

Fig. 2. Average sizes of strands of different varieties of oilseed flax

However, the sizes of the strands along the length of the stem in different varieties of oilseed flax were

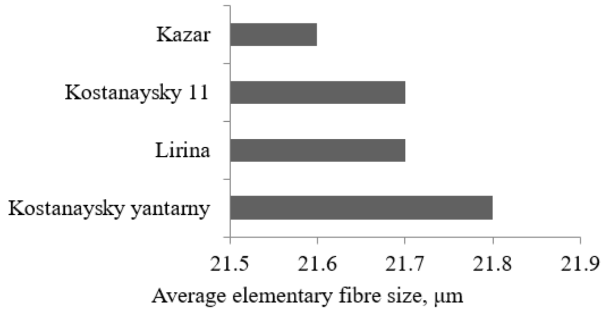

Fig. 3. Average sizes of the elementary fibre of various varieties of oilseed flax

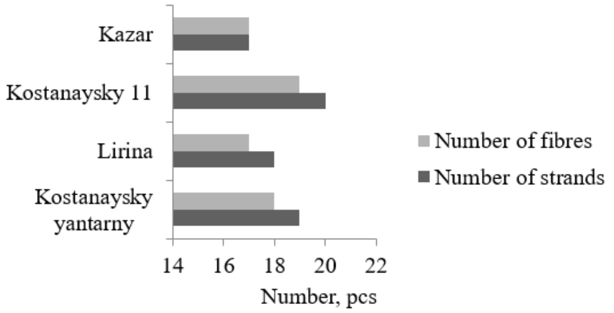

Fig. 4. The number of strands on the cut stems and fibres in the strand along the length of the stem of various varieties of oilseed flax

different. The larger strands are located in the butt part of stem, and towards the top they are slightly reduced.

As for the size of the elementary fibres, they are in different varieties of oilseed flax have approximately the same size, and for the elementary fibres of oilseed flax, the tangent shape is characteristic. Changing along the length of the stem, the size of the elementary fibres decreases from the butt to the top. This indicates that the fibre extracted from the top and butt parts of the stems will have different technological properties.

The analysis allowed to establish that the maximum number of strands on the cut of the stems of the studied varieties of oilseed flax is observed in the variety Kostanaysky 11. However, along the length of the stem, the number of strands in different zones varies significantly.

Determination of the chemical composition of oilseed flax straw

To determine the chemical composition, the raw material was pre-crushed with scissors and an average sample was prepared. The mass fraction of extractive substances (extragent – diethyl ether) – wax glaze, the mass fraction of acid-insoluble lignin, and the mass fraction of cellulose by the Krushner method were determined. The chemical composition of oilseed flax straw is shown in **Table 4**.

Comparison of the results presented in **Table 4** shows that thick stems are characterized by a lower content of cellulose than thin homogeneous straw in general. In addition, the stems have an increased value of the mass fraction of acid-insoluble lignin, which provides special strength and creates difficulties for grinding.

The obtained results of the chemical composition of oilseed flax straw, namely: the cellulose content in the range from 46.90% to 48.85%, ash content at the level of 1.82-3.41%, acid-insoluble lignin from 21.52% to 23.10% indicate the possibility of obtaining cellulose directly from oilseed flax straw.

Research of technological properties of fibre

The main technological properties of straw and fibres of various varieties of oilseed flax were investigated. In particular, the fibre content, its linear density, the relative breaking load of the fibre, and the fibre defect were determined. Data on the technological properties of textile flax were taken for control. A comparative study of the technological characteristics of the stems and fibre showed that the fibre content in the stems of oilseed flax is on average 23-25% less than the indicators of textile flax, which are presented in **Table 5**.

Comparative analysis of the values of characteristics and properties showed that an important indicator of the technological value of the fibre is its linear density. On average, the linear density of oilseed flax fibre is 1.3 -1.4 times higher than that of textile flax.

Extraction of fibre from oilseed flax straw

Then conducted experimental studies on the developed technology to determine the yield of fibre and the degree of purity of the fibre from the shive. 50 kg of oilseed flax straw was minced on a crushing machine,

Table 4. Chemical composition of oilseed flax straw

Name of raw materials	Wax glaze,%	Ash content, %	Lignin, %	Cellulose,%
Kostanaysky yantarny	2,40	2,37	22,85	47,29
Lirina	2,48	1,82	23,10	46,90
Kostanaysky 11	2,36	3,41	21,79	48,85
Kazar	2,12	2,74	21,52	48,03

Table 5. Value of the main technological characteristics of straw and fibre properties

Studied characteristic or properties	Technological characteristics of straw and fibre properties				
	Kostanaysky yantarny	Lirina	Kostanaysky 11	Kazar	Textile flax
Fibre content in the trust, %	23,3	23,3	23,6	20,2	30,8
The linear density of fibres, tex	9,2	8,7	8,9	9,3	6,4
Breaking load of the fibre at an inter-clamp distance of 100 mm, N	4,7	4,2	4,5	4,3	8,2
Defectiveness	1,11	1,07	1,09	1,1	0,87

Table 6. Fibre yield at the processing stages

Processing stages	Value
Weight of the initial sample, kg	50
Weight after the crushing machine, kg	31,85
Yield on the crushing machine, %	63,7
Weight after scutching machine, kg	26,75
Yield on the scutching machine, %	53,5
Weight after the hammer mill, kg	19,75
Yield at the hammer mill, %	39,5
Fiber weight after the shaking, kg	9,75
Yield at the shaking, %	49,4
The total yield of fibers from straw, %	17,8

Table 7. Physical and mechanical properties of fibre by processing stages

Processing stage	Indicators	Value
Crushing machine	The linear density of fibres, tex	62
	Fibre length, mm	92,8
	Content of (shives),% /unseparated fibre	61/29
Scutching machine	The linear density of fibres, tex	46
	Fibre length, mm	70,9
	Content of (shives),% /unseparated fibre	57/28
Shaking machine	The linear density of fibres, tex	15
	Fibre length, mm	52,7
	Content of (shives),% /unseparated fibre	5
Fibre diameter, micron		14,25

processed on a scutching and shredding machine, then cleaned on a shaking machine. The moisture content of the straw at the entrance to the crushing machine was 8.6%. The yield of the obtained fibre was determined by the stages of processing, the results of which are presented in **Table 6**.

Analyzing the results of experiments, it can be noted that the yield of fibre after primary processing of oilseed flax straw was 17.8%. The physical and mechanical properties of the fibre at the stages of re-processing, in particular, the linear density, length, and content of the shives, were studied. The results of the research are presented in **Table 7**.

By results of researches it can be noted that the linear density of fibre after crushing was 62 tex, and after shaking decreased to 15 tex, fiber length decreased on average 2 times. The content of the shives has decreased from 61% to 5%. It was found that increasing the duration of the fibre shaking process leads to an increase in the degree of cleaning from shives. According to the obtained data, it can be concluded that the developed technology allows to obtain fibre from oilseed flax straw with certain characteristics and for various applications, depending on the quality of the raw material.

Optimization of the fiber extraction process

The process of extracting fibre from oilseed straw requires the use of modern methods of mathematical modeling and optimization. Using such methods allows to reduce the time of research, the number of experiments and identify the best technological modes of the processes under consideration. To identify the optimal conditions for conducting processes in enlarged tests, mathematical processing of experimental data was performed to obtain regression equations, on the basis of which the process was optimized.

After the canonical transformation models of the second order were obtained for the regression equation in canonical form, based on which built the model in three-dimensional space representing a plane, which characterizes the dependence of the speed of passage of material through crushing rollers (v, m/min), frequency of rotation of the working body of the disintegrator (n, min^{-1}), the number of oscillations of cylinders of the shaking field (*c,* sw/min) influencing the optimization criteria – the fibre yield (ŋ, %).

Thus, the regression equations for the process of extracting fibre from oilseed flax straw, for coded values, will take the following form:

$y_1 = 17,84283618 + 0,122098x_1 + 0,327058x_2 + 0,151378x_3 - 0,3875x_1x_2 + 0,1875x_1x_3 + 0,1875x_2x_3 - 0,32373x_1^2 - 0,25317x_2^2 - 0,18261x_3^2$

After decoding the independent variables in the equations we get the regression equations for natural values of the factors:

$\eta = 7,3182 - 0,27355v + 0,02409n + 0,018315c + 0,0003875vn + 0,00075vc + 0,00008nc - 0,00324v^2 - 0,000025n^2 - 0,00029c^2$

Fisher's test $F_p = 3,82$.

Thus, given that the model $F_p < F_{table}$ of the technological efficiency of the process of obtaining fibre from oilseed flax straw can be considered adequate with a 95% confidence probability. **Figs. 5**-**7** show graphical representations of dependency graphs.

The analysis of three-dimensional spatial models shows, which are shown in **Figs. 5**-**7**, that the necessary values of the optimization criterion are achieved in the search area under consideration. This means that the variation levels of input factors when planning experiments are taken correctly enough.

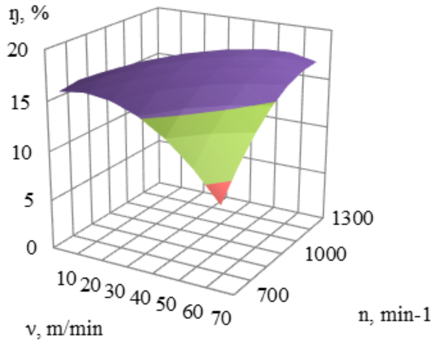

Fig. 5. Three-dimensional model in space that characterizes the dependence of $y_n=f(v, n)$ on the speed of material passing through the crushing rollers (v, m/min) and the speed of rotation of the disintegrator working body (n, min^{-1}) on the fibre yield

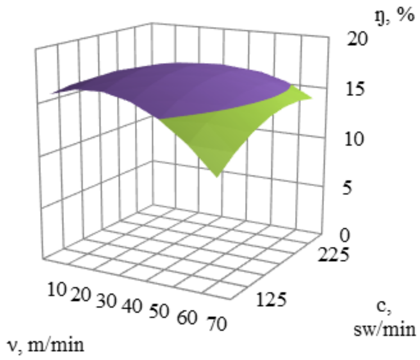

Fig. 6. Three-dimensional model in space that characterizes the dependence of $y_n=f(v, c)$ on the speed of material passing through the crushing rollers (V, m / min) and the number of swings of the shaking field rollers *(c,* sw/min) on the fibre yield

The analysis of the presented graphs showed that on the three-dimensional model in the space there are optimal regions of variable values v (m/min), *n* (min^{-1}), *c* (sw/min), at which the technological process of obtaining fibre from oilseed flax straw is carried out with optimal values ŋ (%).

The given dependences on the variable parameters of the technological process for obtaining fibre from oilseed flax straw - v (m/min), n (min^{-1}), *c* (sw/min) allow to predict with sufficient accuracy the change in the values of the optimization criteria *y* in the studied range of factors - fibre yield (ŋ, %). On the basis of experimental studies and mathematical modeling of the process of extracting fibre from oilseed flax straw, the following optimal values were established: the speed of

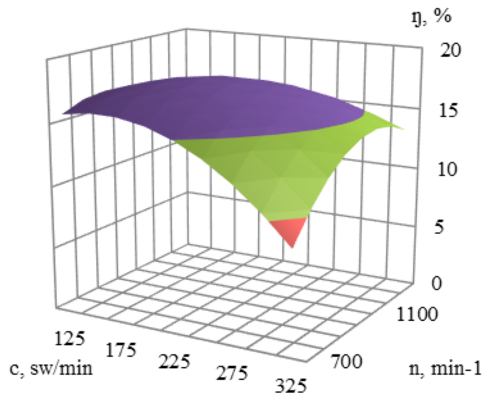

Fig. 7. Three-dimensional model in space that characterizes the dependence of $y_n=f(n, c)$ on the frequency of rotation of the disintegrator working body (*n*, min^{-1}) and the number of swings of the shaking field rollers (c, sw/min) on the fibre yield

material passing through the spiral rollers 30 m/min, the rotation frequency of the working body of the disintegrator 1000 min^{-1}, the number of the roller swings of the shaking field 125 sw/min affecting the optimization criteria - the fibre yield of 17.8%. Thus, the results obtained will allow to optimize the process under study by applying the developed mathematical model.

CONCLUSIONS

The obtained results of the chemical composition of oilseed flax straw indicate the possibility of obtaining cellulose directly from oilseed flax straw. According to the results of research, it was found that increasing the duration of the fibre shaking process leads to an increase in the degree of cleaning from shives. Comparative analysis of the values of characteristics and properties showed that such an important indicator of the technological value of the fibre as the linear density is 1.3-1.4 times greater than that of textile flax. The established optimal modes of fibre extraction by developing a mathematical model of the process allowed to optimize the process under study. Thus, the study of the possibility of obtaining fibre from oilseed flax straw by mechanical processing, the study of the technological properties and suitability of the resulting fibre for technical use showed that the developed technology allows to obtain fibre from oilseed flax straw with certain characteristics and for different applications, depending on the quality of the raw material.

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