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Research of flax fiber production by innovative technology

Yurii Berezovskyi*
Doctor of Technical Sciences, Professor
Kyiv National University of Construction and Architecture
03037, 31 Povitrianykh Syl Ave., Kyiv, Ukraine
https://orcid.org/0000-0002-9645-2743
Tetyana Kuzmina
Doctor of Technical Sciences, Professor
Kherson National Technical University
29016, 11 Instytutska Str., Khmelnytsky, Ukraine
https://orcid.org/0000-0002-6113-1923
Natalia Lialina
Doctor of Technical Sciences, Professor
Kyiv National University of Construction and Architecture
03037, 31 Povitrianykh Syl Ave., Kyiv, Ukraine
https://orcid.org/0000-0002-9364-0925
Galina Boyko
PhD in Technical Sciences, Associate Professor
Kherson National Technical University
29016, 11 Instytutska Str., Khmelnytsky, Ukraine
https://orcid.org/0000-0001-8773-5525
Tetiana Holovenko
Doctor of Technical Sciences, Senior Researcher
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-1792-9364

Abstract. Modern needs of consumers require expanding the range of environmentally friendly products, as well as providing Ukrainian industry with raw materials for the manufacture of military and special-purpose goods. It can be done with the help of Ukrainian production of fibrous flax products using new technologies and innovative developments. The purpose of the work was to search for improved production conditions for processing long-fibred flax and develop a method of processing trusts without dividing the fiber into long and short to provide the national producer with a high-quality fibrous product with the possibility of expanded conditions for its use. An analysis of the technical and technological capabilities of fiber producers was carried out, consumer demand for natural fiber was determined, theoretical approaches to cleaning the fibrous material were clarified to achieve this goal. The study of qualitative and quantitative characteristics of the fibrous product were carried out according to organoleptic and instrumental methods of evaluation in the conditions of production control. The most significant factors of influence, which have the greatest influence on the passage of the processes of breaking stems and scutching fibrous raw flax were determined during the a priori experiment. Regression models of the boonness

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**Corresponding author*

process in different parts of the proposed equipment were obtained through the use of software and the use of regression analysis by modeling the technological process of obtaining the same type of fiber according to the developed innovative components. This process was designed to determine the rational parameters of the process of cleaning the fibrous product. The conditions of use of the proposed equipment and the influence of the work of different parts of the equipment on the economic result of the processing of the long-fibred flax straws were clarified in the work. Directions for further use of the obtained fibrous product were also established. The obtained results of research can help the national producer of goods of everyday use and special and military purposes to solve the problem of providing high-quality fiber raw materials, to increase the competitiveness of Ukrainian products in the internal and foreign markets of goods and services

Keywords: innovations; raw material; fibrous product; breaking; scutching; quality; boonness

Introduction

Ukraine has not lost the desire to cooperate in a single European family of civilised countries, where all issues are resolved in a compromise, and not by armed means. Although the period from 2014 to 2024 was characterised by constant aggressive actions by the Russian Federation. The European Union supported this aspiration and contributed to the integration of the Ukrainian economy into the overall economic structure of Europe.

The EU textile development strategy was put into effect and taken into account by the Ukrainian light industry in such a situation. This strategy was based on reducing environmental impact and promoting sustainability and transparency in the value chain of the final product. The strategy Challenges for Ukrainian producers in view of the EU Textile Strategy-2030 (2023) provided for the reform of legislation in the direction of real technical implementation with a change in the technical regulation of the economy, the creation of demand for environmentally friendly textiles both from individual consumers and from government agencies through the introduction of specific measures to create a competitive advantage with sustainable high-quality textiles. The main components of this strategy were improving the efficiency of this sector, covering the field of innovation and digitalisation, skills development, support for startups and internationalisation, access to open energy through significant funding.

Since 2014, Ukraine has gradually increased interest in the production of military and special purpose clothing from both the private sector and the state. Lubofiber crops acquire special importance in modern conditions of growing demand for ecological goods and increasing demand from manufacturers of military and special purpose products. Flax, hemp, and jute were sources of natural fibers that can be used in various industries. The expansion of production capacities and the increase in the volume of processing of lubofiber crops was an important step in providing raw materials for both the light and textile industries. Specialised materials can be used both in the defense sector and in other areas of special purpose.

Authors H.A. Al-Gaoudi *et al*. (2024) noted that natural fibers from lubofiber crops can be used in the manufacture of environmentally friendly fabrics. The scientists highlighted various engineering techniques and mechanisms adopted to develop a sustainable flexible composite based on natural fibers as an alternative to leather material.

Natural cellulose-based fibers, such as lubofiber crops, have unique properties, namely: attractiveness in the manufacture of products of various technical applications, have a high modulus of elasticity, tensile strength and moderately high friction coefficient, adequate air permeability and environmental friendliness, abrasion resistance and light weight. S. Basak *et al*. (2024) noted that the addition of natural fiber to the rubber composition increases its tensile strength, coefficient of friction, the use of natural fiber components in leather alternatives. It also improved flexibility indicators, thermal conductivity, and throughput, made the material softer, and improved protection against odor, moisture, and dust. All of the above were very important indicators for end users of products.

Scientists R.M. Iqbal *et al*. (2024) and R. Natesan & P. Krishnasamy (2024) revealed the mechanisms for improving the properties of composites reinforced with natural fibers and noted that they were a promising alternative to synthetic fiber composites due to their favourable environmental characteristics, economic efficiency and decent mechanical properties. In addition, approaches to mitigate the problems associated with moisture absorption, degradation of structural integrity and lack of homogeneity of fibers were disclosed by the authors.

Products, made from canvases, obtained from blended yarns, began to enjoy significant demand among modern consumers due to their unique properties (2013-2023). These canvases combine the advantages of different fibers, which ensured their popularity in the textile industry, contribute to their demand due to the presence of improved characteristics. Researcher U. Bilen (2021) noted that flaxseed fabrics mixed with artificial cellulose fiber do not have significant differences in heat absorption compared to other fabrics, however, this contributes to improved air permeability, bending and shear ability. The fabric, woven from 80% lyocell and 20% flax, showed the best results in terms of heat and steam permeability, as well as the ability to form and elongate. The obtained data showed that the fabric with 100% cotton base, 80% lyocell and 20% linen weft provided optimal temperature indicators and comfort in the production of bed linen.

In the scientific work of N. Senthil & B. Dhurai (2021) noted that linen yarn produced by wet spinning and treated with OWL softener has improved softness, elongation, bending, stiffness, fleeciness and unevenness values. This made it possible to get a knitted fabric from the threads of this yarn and demonstrate a good knitting without any fabric defects.

Combining the properties of different materials was an effective strategy for creating textiles that combine comfort and functionality. Natural bast fibers provide pleasant tactile properties, air permeability, hygiene, hypoallergenicity, while artificial, synthetic materials give strength, wear resistance, crease resistance and ease of care. This made this combination ideal for the production of products in the sphere of defense and special purpose.

N.P. Bukhonka (2023) noted the advantages of combined materials in knitwear, focused on the "practical" advantages of synthetic fibers in combination with the environmental and tactile properties of natural ones, pointed to a change in the structural characteristics, air permeability and creasing of knitted products from all types of yarn in operation and after washing.

As noted by L. Navone *et al*. (2020), textile waste, which combines natural and synthetic fibers, consisting of mixed textile materials was a serious environmental problem. Only a small part of the products of the fashion industry was collected, reused or recycled. The processing of textile waste is a difficult task due to the need to separate the fibers into separate components, which is complicated by the multi-component structure of clothing. Critical environmental conditions such as humidity, temperature, ventilation and allergic reactions from materials can affect human health. The use of natural components in products that provide optimal conditions for the psychophysiological state and functioning of the body is important for consumers. Therefore, the development of the processing branch of light industry should include the creation of mechanisms for expanding the range of modern products using natural fibers of bast crops, which are traditionally grown in Ukraine.

The purpose of the study was to search for opportunities to improve the processing conditions of long-fibred flax to provide the Ukrainian producer with a significant volume of natural fiber products, to improve the qualitative and quantitative characteristics of the light industry processing industry. For this purpose, the following tasks were determined: to analyse the factors of influence on the processes of processing bast raw materials; to identify the factors that most affect the qualitative and quantitative characteristics of the processing of stem material; to develop mechanisms and method of processing long-fibred flax for providing the national producer with high-quality fibre of various functional purposes.

Materials and Methods

The object of the study was the flax straws of long-fibred flax, grown in the northern regions of Ukraine. Factors of influence on the process of processing stalks of long-fibred flax, factors of formation of qualitative and quantitative characteristics of fibrous products during processing of stem material of bast raw materials were taken into account.

Production tests using experimental equipment at processing enterprises of Lviv and Zhytomyr regions were conducted to confirm the results of theoretical studies in 2020-2022. The efficiency of the work was to indicate an improvement in the processing of bast raw materials and the quality characteristics of the resulting fiber with the possibility of further expanding the scope of its application. Processing and analysis of the obtained research data was carried out in 2023-2024. Long-fibred flax of modern varieties – Esman, Gladiator, which according to the Order of the Ministry of Agrarian Policy and Food of Ukraine No. 306 (2018) were included in the Register of plant varieties of Ukraine and were used for experimental research as bast raw materials.

The requirements of the state standards of Ukraine were met during the study of the processing process of long-fibred flax stalks: DSTU 4015-2001 (2002), DSTU 4149-2003 (2004), DSTU 4511:2006 (2006), DSTU 5015:2008 (2009). The requirements described in DSTU ISO 2370:2009 (2011), ISO 2370:2019 (2019) and ASTM D7076-10 (2021) e1 (2021) have also been met.

The study of the process of processing the stem material of long-stem flax trusts was carried out under the same conditions as the mechanical processing of oilseed flax to comply with the principle of unambiguity. The degree of stock compress, breaking load, fiber output, output of chaff, which most characterise the processes for producing fiber and its final quality, were chosen to study the process of processing flax stalks and evaluate the quality of fiber products the most important indicators. Mathematical methods of experimental planning were used to determine the intensity of the influence of factors on the process of mechanical processing of bast raw materials and the separation of non-fibrous impurities from the fibrous part of the stem. In particular, a complete factor experiment, the value of the optimisation parameters of which for all possible combinations of levels of factor variation, was determined during implementation. This method allowed to investigate the influence of various factors on the process, since it implemented all possible combinations of levels of the studied parameters. The implementation of all possible combinations of levels of factors made it possible to study the process in detail and provided scientifically sound conclusions on the most significant factors that affect the quality of mechanical processing of long-fibred flax. The study performed rotable second-order planning (Box plan). The Student's test was used to assess the significance of long-fibred flax deboning process.

The dependence of the content of chaff in linen fiber on changes in the parameters of significant factors that affect the processing of this bast raw material was characterised as a result of regression analysis. Modern means of computer modeling and mathematical data processing were used to analyse and obtain regression equations. The main tools were SOLIDWORKS, MathCAD-2015, Microsoft Office Word 2007, and Microsoft Office Excel 2007. The use of these software tools made it possible to automate calculations and create accurate mathematical models that reflect the influence of various factors on the efficiency of the processing of bast raw materials.

Results and Discussion

Since the beginning of 2022, the Ukrainian light industry has faced a controversial situation, with production following a downward trend. In 2023, the number of light industry producers in Ukraine increased by 22%, reaching more than 19700 companies, of which 72% were individual entrepreneurs, and large enterprises make up only 1% of the total, which indicated a significant dominance of small and medium-sized businesses in this sector of the economy (The 10 largest manufacturers of clothing, footwear and textiles in Ukraine..., 2024). However, despite the growth in the number of producers, their total income in 2023 decreased by 13%, amounting to 47.1 billion UAH. Most of the income was received by clothing manufacturers, who earned 23 billion UAH. This pointed to the important role of this sector in light industry. The unstable situation in light industry in sub-sectors can be seen from the data of Ukrlegprom on procurement for the Armed Forces of Ukraine and other areas of work (2024).

It is worth noting that manufacturers relied on the production of clothing for the military and sales abroad in 2022-2024. Ukrainian light industry often faced fierce competition in the internal fashion market, despite the growing number of manufacturers. The influx of cheap goods from Asia and the return of Western mass-market brands were the main factors that made it difficult to stop. Products from Asian countries were often offered at lower prices, making them more attractive to many consumers. Western brands have strong marketing strategies, well-known brands and large-scale distribution channels, which made it difficult for Ukrainian manufacturers to compete in such an environment.

The decline in production indicators in light industry was observed in 2024. This was due to both internal challenges and global market processes. Light industry felt these negative processes more sharply and with acceleration. Although the decrease in production volumes is typical for the entire processing industry in Ukraine. The situation in the Ukrainian light industry deteriorated significantly in the second quarter of 2024. According to research V. Volokita (2024), 33% of companies reported a reduction in production due to the following factors: lack of labour, power outages, rising prices for raw materials. This significantly affected the overall production indicators of the industry.

New promising areas of light industry were beginning to take shape in Ukraine, despite a 13% decline in revenues in 2023 and the challenges associated with a full-scale war. They were not only focused on internal market demand, but were also export-oriented, which opened up additional opportunities for further growth. Key areas: production of military products and special clothing for law enforcement agencies, the demand for which has increased sharply due to the war; production of home clothing, which was in demand among ordinary consumers; production of wedding dresses, caused by increased demand from foreign orders. In this case, you can use the experience of scientists in obtaining a variety of materials. For example, L. Kohan *et al.* (2019) noted that natural fibers from lubofiber crops can be used in the manufacture of artificial leather. Scientists L. Samant *et al.* (2023) revealed ways to improve the mechanical properties of natural rubber composites by using reinforced flax natural fiber with a 9% and 27.4% increase in tensile and breaking strengths in the NaOH-treated and flax fiber-reinforced composite. S. Huo *et al.* (2013) noted improved strength characteristics of polymer matrix composites using reinforced flax fiber. At the same time, it is worth noting that the treatment with acrylic acid increased both the interfacial shear strength and the interlayer shear strength by about 30% compared to untreated linen composites. In a scientific paper, the authors J. Summerscales *et al.* (2010) argued that bast fibers were widely used in the textile industry and were increasingly being considered as reinforcing materials for polymer matrix composites, because they were perceived as "stable". Scientists have noted that predicting the properties of natural fiber-reinforced composites in view of their potential application and environmental considerations can accelerate or limit the adoption of these composites in application.

Clothing and textiles always play a key role in times of economic crisis, while these products are essential goods. Consumers focus on basic needs in conditions of economic instability, but textiles and clothing remain indispensable. This can make light industry one of the most stable sectors of the economy, as well as the processing sector, engaged in the production of natural fiber from bast crops.

Ukraine can use this as an advantage in the process of becoming an economy, since the production of clothing and textiles from natural fiber can not only satisfy internal demand, but also open up new opportunities for export. This is especially true for niche segments, such as workwear, wedding dresses or innovative textiles. In addition, light industry is a labour-intensive industry. It can create jobs, supporting the country's economy during the war. According to the research Ukrlegprom on procurement for the Armed Forces of Ukraine and other areas of work (2024), clothing and textiles not only quickly find their consumers, but also make the production of light industry products a source of income and stability in international trade (Fig. 1).

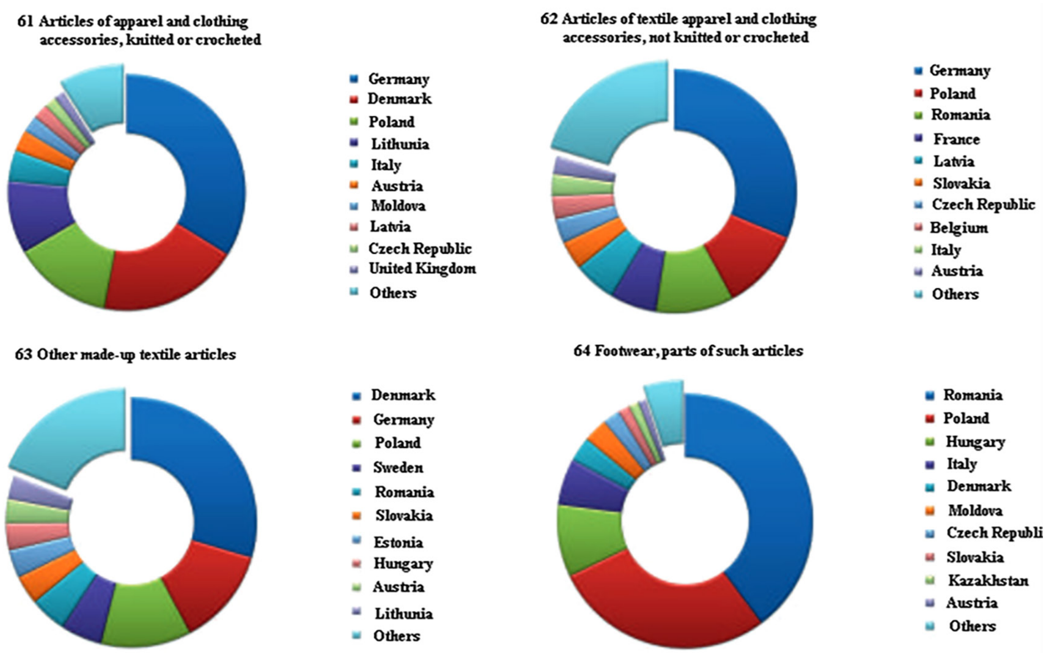

Figure 1. *Top countries of textile exports of Ukraine in 2022*
Source: *based on Ukrlegprom. Fashion & Production (2023), Official website of Diia. Business (2024)*

According to Figure 1, it can conclude that Ukrainian light industry products were in demand in Western Europe, in the countries of high fashion legislators, such as France, Italy, Germany. This gave Ukraine the opportunity to use the current trends in the development of the industry, to perceive the needs and requirements of consumers on time, to navigate the changes in the market of goods. The spread of the trend of using environmentally friendly products acquired in the world in the period 2000-2015. This situation can serve as a good guarantee in expanding its position in the market of goods and popularising the Ukrainian brand of manufacturers of light industry products, which largely used linen fiber (Fig. 2).

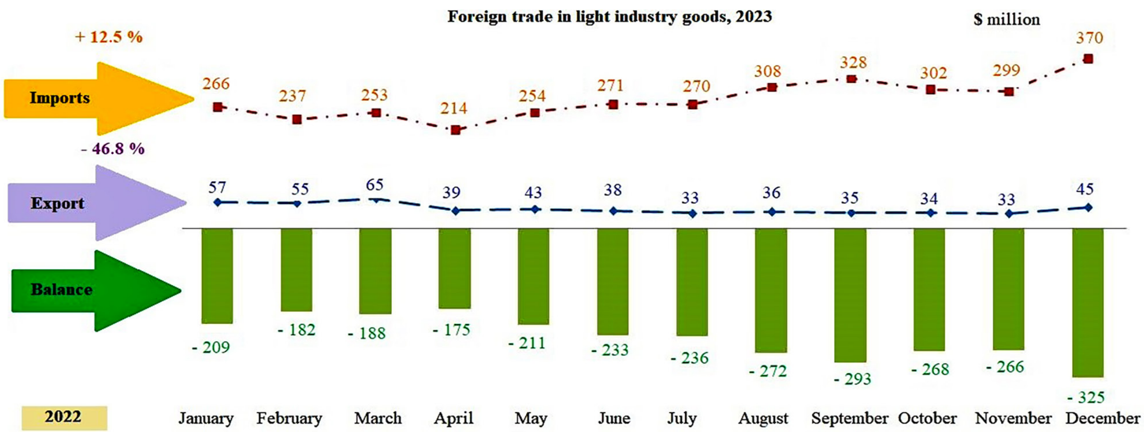

Figure 2. *Foreign trade in light industry goods for 2023*
Source: *based on Ukrlegprom on procurement for the Armed Forces of Ukraine and other areas of work (2024)*

The results of trade in light industry goods for 2023 indicated that the military situation in Ukraine affected the results of trade activities, reduced or suspended production capacities, canceled tender and procurement procedures, and reduced the volumes of contracts. All this influenced the increase in the negative balance. It should be noted that such a situation may become the basis for the interest of Ukrainian manufacturers of light industry in the production of demanded military and special-purpose products using linen fiber potential. Important for the conduct of state policy in modern conditions of management is the preservation of jobs.

Association "Ukrlegprom" according to the source Ukrlegprom on procurement for the Armed Forces of Ukraine and other areas of work (2024) reported and provided industry information to the newly created state enterprises of the Ministry of Defense of Ukraine "State Logistics Operator" and "Defense Procurement Agency" to ensure maximum involvement of manufacturers to participate in procurement. Namely: in the context of manufacturing enterprises that produce raw materials for finished products and are strategic for Ukraine's light industry; in the context of manufacturing enterprises that produce finished products, grouped according to a homogeneous technological production process; criteria for Ukrainian manufacturers according to the Procedure for granting the status of national producer to an enterprise, confirming or revoking this status (2022). Figure 2 highlighted the special role of producing strategically important goods. The state ready to pay particular attention to the raw materials used in their production. This serves as an additional factor encouraging the processing of bast raw materials, emphasising the need to improve the technological processes involved in the processing of long-fibred flax (Yaremova *et al*., 2024).

Ukraine was one of the world leaders in the production of flax fiber until 1992, providing more than 100 thousand tons of raw materials annually. This accounted for 13-16% of the world volume. Approximately, 40 thousand tons of flax fiber were processed by Ukrainian enterprises, while the rest were exported for more than 40 million USD. Flax cultivation was a key agricultural sector, ensuring high profitability for both producers and processing enterprises. Long-fibred flax products constituted a significant portion of monetary income from crop production, contributing to the economic development of rural areas, particularly in Polissia, where this crop was traditionally grown. Long-fibred flax provided three types of products: fiber, seeds, and chaff (Berezovsky, 2016).

Climate changes in the direction of warming, the complex technological process of processing flax, metal capacity and energy intensity of processing equipment for 2005-2010 reduced the importance of processing the stems of this crop, made it more relevant to grow oilseed flax, especially in the southeastern regions of Ukraine. However, the industrial production of long-fibred flax products has significant potential, which must be realised through modernising the technical facilities of the flax processing industry, applying advanced stem processing technologies, and integrating innovations at all stages of obtaining natural fiber while reducing energy and material consumption (Lialina *et al.*, 2023; Didukh *et al.*, 2024).

The mechanical processing of bast crops, such as flax and hemp, has been the subject of research by numerous scientists, who have made significant contributions to the development of the theory and practice of stem material processing. Their work has improved technological processes and enhanced the efficiency of producing bast-fiber materials. For instance, B.V. Lesyk (1969) noted that flax fiber is a completely environmentally friendly, natural folding material, does not create a negative impact on the environment after disposal, it is an ideal universal raw material for the production of clothing, bed linen and technical materials. However, its use was accompanied by certain difficulties, such as high production cost and the ability to crumple easily, which required manufacturers to optimise production processes and use modern technologies to eliminate shortcomings, which can increase the competitiveness of flax-containing products in the consumer market.

Authors T.M. Holovenko *et al.* (2018) and G.A. Boyko *et al.* (2018) pointed out that outdated equipment and technologies are used in Ukraine's industrial production of flax and hemp fiber, negatively impacting the economic state of enterprises. Therefore, updating the technical and technological base was urgently needed. P.M. Valko (2011) emphasised the need to create more efficient crumpling rollers to improve the process of crumpling, while T.M. Holovenko (2013) demonstrated that nonwoven materials from oil flax straw can be produced using foreign equipment adapted to a proposed technological scheme for obtaining fibrous products. R.N. Helyazetdinov (2009) stated that to achieve high-quality fiber products, it was necessary to use specialised machines and units both sequentially and simultaneously, significantly improving fiber production efficiency. According to S. Yaheliuk *et al.* (2022), the main requirements for a processing line were complexity and versatility. By employing various technical developments and improvements, production facilities obtain both parallelised and disoriented fibers, enabling manufacturers to apply different technologies depending on the final product desired. Consequently, research focused on developing technological innovations and refining existing processes to produce uniform flax fiber.

The development and application of innovative technical and technological solutions in the mechanical processing of long-fibred flax were based on improved components of crumpling and scutching sections of processing equipment. These advancements significantly enhanced the efficiency of fiber separation and cleaning from non-fibrous components, positively influencing the quality of the final product and expanding its application areas (Berezovsky, 2016; Berezovsky, 2018).

The key stages of the new technology for obtaining uniform fiber from bast crops include (Fig. 3):

1. Unwinding of rolls on a reel, which provides for the supply of bast crop stems from rolls for further mechanical processing.

2. Crumpling with rolls of various types with simultaneous stretching, using proposed rolls of ribbed, slatted, disc, and comb types to soften the stems and separate the fiber from the shives while simultaneously stretching the fibers. This ensures an even distribution of fibers in the processed layer for further processing of the raw material.

3. Scutching, performed using a proposed scutching drum design equipped with beaters and knives, effectively cleaning the flax fiber from impurities.

4. Final fiber cleaning, using shaking machines equipped with shaking-vibrating devices to remove residual non-fibrous materials, significantly improving the quality of the final fiber product.

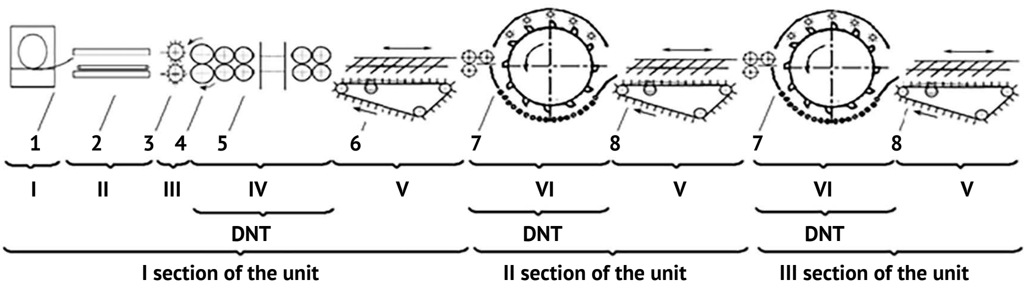

***Figure 3.** The technological scheme of the experimental unit for obtaining uniform fiber from bast crops and the equipment and equipment for its implementation*

***Note:** DNT – device of a new type; I – unrolling section; II – drying section; III – layer-forming section; IV – crumpling section; V – shaking section; VI – scutching section; 1 – bundle unwinder; 2 – drying machine; 3 – peg mechanism; 4 – pair of enlarged-diameter rolls; 5 – breaking machine; 6 – preliminary cleaning shaking machine equipped with a vibrating device; 7 – scutching unit; 8 – shaking machine equipped with a vibrating device*

***Source:** developed by the authors*

Due to the processing of the stem material of long-fibred flax with a wide differentiation of mechanical actions, the integrity of the stems was disrupted, the bond between the fiber and the wood was broken. Conditions for effective separation of the fibrous part from the wood part are formed. A special role in the processing of stem material was played by scraping and thinning the raw material layer on cleaning rollers. Their action, in combination with a shaking device, allows for uniform processing and cleaning of the fibrous material. The integration of a shaking-vibrating device between the processes of breaking and scutching enables more effective removal of woody particles and other impurities, reducing the loss of valuable fiber and improving its quality.

Thanks to the proposed structural innovations in the breaking and scutching zones of the processing equipment, it became possible to achieve a higher-quality separation of fibrous material from non-fibrous components. This not only improved the purity of the obtained fiber, but also increased the productivity of the process. The improved quality of the fiber allows it to be used in a wider range of industrial and consumer products, expanding the market and enhancing the economic appeal of bast crop production. A significant number of technological factors and parameters of the working bodies of the equipment affect the efficiency of processing the long-fibred flax trusts. The efficiency of raw processing and the formation of fiber quality characteristics depends on these factors.

The depth of entry of the riffles; density of raw material loading; fiber layer thickness; linear velocity of material movement in flax pairs; grooving pitch; moisture content of raw materials; number of corrugations of crushing rolls; the state of the bast trusts; method of feeding a crushing unit; specific pressure in a pair of crushing rolls were determined during studying the process of crushing. Their influence on the process of processing the stems of linen raw materials was considered.

The three most significant factors were determined by the results of the a priori experiment. They have the greatest impact on the quality of passing the stems of long-fibred flax:

1. Specific pressure in the breaking roller pair. This determines the forc,e with which the rollers compress the raw material, significantly affecting the efficiency of separating fiber from woody material and the extent of fiber damage, when excessive pressure is applied.

2. Raw material moisture content. This critically impacts the mechanical processability of the stem material, influencing efficiency due to the excessive flexibility of wet raw material or the potential damage to overly dry stems.

3. Degree of retting. This indicates the readiness of the raw material for processing and directly affects

quantitative and qualitative losses of the fibrous part of the stem.

Factors influencing scutching, such as drum rotation frequency, raw material layer thickness, spacing between flail bars and the grid, spacing between the scutching knife and flail bar, retting degree, raw material moisture content, spacing between the scutching drum and feed unit, raw material density, the number of flail bars on the drum, feeding speed, material preparation level, material layer structure, and installation design features, were analysed for their impact on scutching fibrous raw flax in the process study.

Three key factors were found to have the most significant impact on the quality and quantity of the fibrous product obtained according to the results of a priori experiment:

1. Scutching drum rotation frequency. This determines the intensity of the scutching process, ensuring effective cleaning without significant quantitative fiber loss at the optimal frequency.

2. Spacing between flail bars and the grid. This impacts the intensity of the flail bars' effect on the raw material, directly influencing cleaning efficiency and minimising fiber damage.

3. Spacing between the scutching knife and flail bar. This determines the precision and effectiveness of separating woody particles from the fiber, significantly affecting fiber losses.

The effects of the identified factors on the processing of flax straw stems, their critical role in shaping the quantitative and qualitative characteristics of the Gladiator and Esman flax varieties were determined during the studies. Change in the quality of the fibrous product was controlled by the content of foreign impurities. This is one of the main parameters that affects the choice of the direction of further use of fiber in the production of final products. Rotatable planning of the second order (Box plans) of the process of mechanical processing of bast raw materials of various parts of processing equipment was applied during the experiment.

The study of the dewatering process in the first part of the processing equipment was carried out with the following parameters:

- specific pressure per 1 linear cm of the stem layer in a pair of crumpling rolls, P = 8.12-11.48, daN/cm;
- raw material moisture content, W = 8.96-19.04, %;
- degree of ripen of trusts, *B* = 2.64-9.36, units.

Regression models of processes of processing of long-fibred flax stalk material in different parts of the proposed equipment were obtained as a result of data processing (Table 1).

Table 1. *Regression models of the process of boonness the fibrous flax product*

Place of determination	Long-fibred flax variety	Regression model
First part of the equipment	Gladiator	$y_1 = 49.834 - 1.201x_1 + 0.547x_1^2 + 0.518x_2^2 + 0.401x_3^2$
	Esman	$y_1 = 48.451 - 1.228x_1 + 0.576x_1^2 + 0.516x_2^2 + 0.403x_3^2$
Second part of the equipment	Gladiator	$y_2 = 3.489 - 0.241x_4 + 0.27x_4^2 + 0.224x_5^2 + 0.219x_6^2$
	Esman	$y_2 = 3.594 - 0.328x_4 + 0.211x_5 - 0.262x_6 + 0.3016x_4^2 + 0.306x_5^2 + 0.306x_6^2$
Third part of the equipment	Gladiator	$y_3 = 1.848 - 0.118x_4 + 0.171x_4^2 + 0.148x_5^2 + 0.148x_6^2$
	Esman	$y_3 = 1.864 - 0.14x_4 - 0.08x_6 + 0.155x_4^2 + 0.153x_5^2 + 0.148x_6^2$

Note: *y_1 – content of boon in fibrous raw material, %; x_1 – specific pressure per 1 linear cm of the stem layer in the breaking roller pair, daN/cm; x_2 – raw material moisture content, %; x_3 – degree of ripen of trusts, units; y_2 – content of boon in fibrous material; x_4 – scutching drum rotation frequency, min^{-1}; x_5 – spacing between flail bars and grid, mm; x_6 – spacing between scutching knife and flail bar, mm; y_3 – content of boon in processed flax fiber*

Source: *developed by the authors*

Regression models describing the process of unchaffyness of flax stalk material of long-fibred flax during its processing in the proposed equipment in its various parts were given in Table 1. Coefficients of the second-order model were determined, and their significance was evaluated using the Student's criterion, excluding insignificant coefficients from the dependency equations. Equations 1 and 2 indicated that the specific pressure on the stem layer in the breaking roller pair significantly affects the unchaffyness process in the first section of the equipment. Equations 3 and 4 revealed that during scutching in the second section, the scutching drum rotation frequency significantly impacts the cleaning process of fibrous raw material. For the Esman variety, the spacing between flail bars and the grid, as well as the spacing between the scutching knife and flail bar, also play a role. Equations 5 and 6 demonstrated the importance of drum rotation frequency during the cleaning process. It should be noted that the process of separating fiber from foreign impurities of the Esman variety was also affected by the amount of dilution between the tip knife and the beating bar.

Figures 4-12 presented response surfaces of regression models for the cleaning process and fiber quality characteristics during the processing of Gladiator and Esman flax varieties.

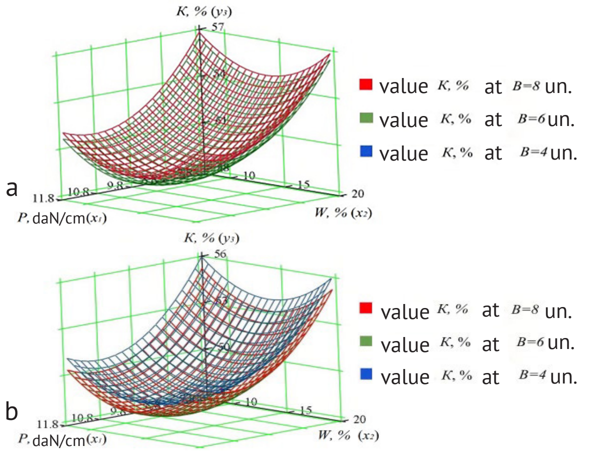

Figure 4. *Response surface of dependence of initial values of boon content index, K, % (y_1) of long-fibred flax trusts of Gladiator (a) and Esman (b) varieties on input factors when considering the levels of the state of the trust, expressed by the degree of tracking B, units in the first part of the proposed equipment*
Source: *developed by the authors*

According to the analysis of the response surfaces (Fig. 4) of the regression model y_1, it can be stated that during mechanical processing in the first section of the proposed equipment, at raw material moisture levels of W = 14% and the retting degree of B = 6-8 units, the lowest content of woody core in the fibrous material of Gladiator (a) and Esman (b) flax varieties was achieved. This occurred at a specific pressure of 9.8-10.8 daN/cm per linear cm of the stem layer in the pair of breaking rollers.

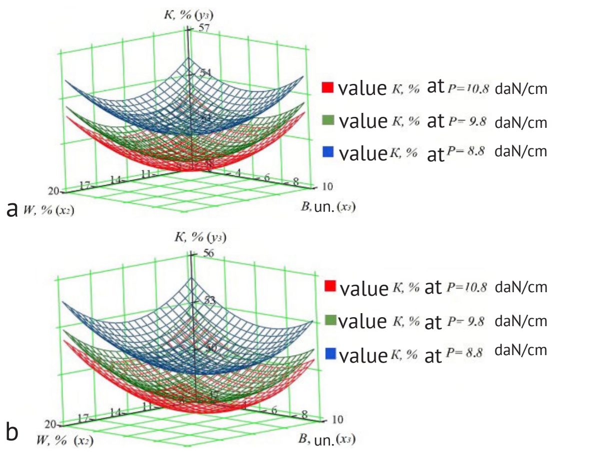

Figure 5. *Response surface of the dependence of output values of the woody core content indicator K, % (y_1) in the flax retting of Gladiator (a) and Esman (b) varieties on the input factors considering the levels of raw material moisture W, % in the first section of the proposed equipment*
Source: *developed by the authors*

According to the analysis of the response surfaces (Fig. 5) of the regression model y_1, it can be stated that during mechanical processing in the first section of the proposed equipment, at a raw material moisture content of W = 14% and a retting degree of B = 6.0 units, the lowest values of boonness in the flax fiber of long-fibred flax of Gladiator (a) and Esman (b) varieties were achieved with a specific pressure on 1 cm of the stem layer in the pair of crushing rollers P = 9.8-10.8 daN/cm.

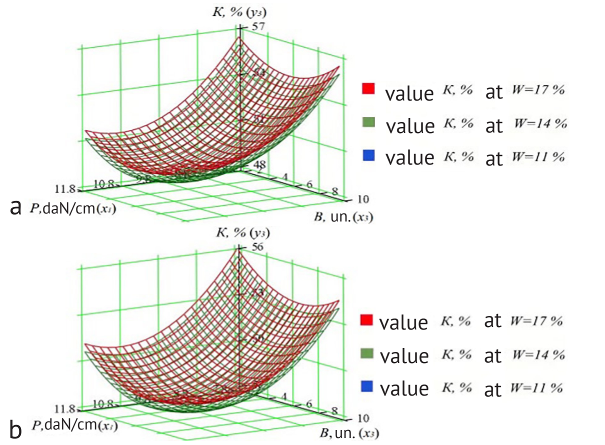

Figure 6. *Response surface of the dependence of output values of the boon content indicator, K, % (y_1), in the retted flax of Gladiator (a) and Esman (b) varieties on the input factors considering the raw material moisture levels W, % in the first section of the proposed equipment*
Source: *developed by the authors*

The analysis of the response surfaces (Fig. 6) of the regression model y_1 demonstrated that at a specific pressure of 9.8 daN/cm per linear cm of the stem layer in the pair of breaking rollers and a ripen degree of 6.0 units during machining in the first part of the proposed equipment. The lowest values of boonness in the flax fiber of long-fibred flax of Gladiator (a) and Esman (b) varieties were observed at the humidity of the raw materials W = 11-14%.

The analysis of the research results and response surfaces of regression models y_1 indicates that, under rotatable planning, the best results of mechanical processing of Gladiator and Esman flax stem material can be achieved at specific pressures of 9.8-10.8 daN/cm, raw material moisture levels of W = 11-14%, state trusts and a ripen degree (B) at 6-8 units. The identified optimal parameters for mechanical processing in the first section of the experimental equipment provide rational values for achieving the lowest woody core content in the fibrous material.

The study of the influence of these factors on stem material processing showed that their effect on the quantitative and qualitative characteristics of Gladiator and Esman flax fibers is consistent. The mechanical processing of the Gladiator and Esman flax varieties was analysed through the constructed response surfaces of regression models for cleaning fibrous material from woody core and foreign impurities in the second section of the proposed equipment, as shown in Figures 7-9.

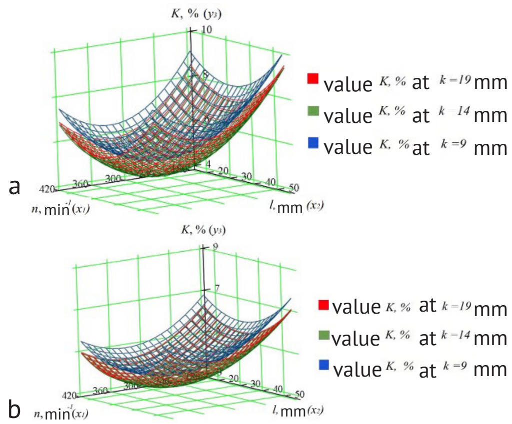

Figure 7. *Response surface of the dependence of output values of the boon content indicator, K, % (y_2) of raw flax of Gladiator (a) and Esman (b) varieties on the input factors considering the clearance between the scutching knife and the batten bar of the scutching drum k, mm in the second section of the proposed equipment*
Source: *developed by the authors*

It can be stated that the the smallest values of boonness of fibrous material of long-fibred flax of Gladiator (a) and Esman (b) varieties was achieved at a clearance between the scutching knife and the batten bar of the scutching drum k = 14-19 mm were obtained during mechanical processing in the second section of the proposed equipment, at a scutching drum rotation speed n = 300 min^{-1} and a dilution value between the scutching drum and the grid of the scutching unit l = 36 mm, according to the analysis of the response surfaces of the regression model y_2 (Fig. 7).

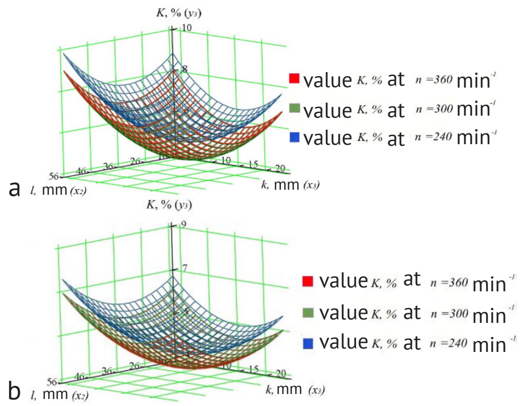

Figure 8. *Response surface of the dependence of output values of boon content indicator, K, % (y_2) of raw flax of Gladiator (a) and Esman (b) varieties on the input factors considering the scutching drum rotation speed n, min^{-1} in the second section of the proposed equipment*
Source: *developed by the authors*

The analysis of the response surfaces (Fig. 8) of the regression model y_2 demonstrates that at a dilution value l = 36 mm between the scutching drum and the grid of the scutching unit, and dilution value k = 14 mm between the scutching knife and the batten bar of the scutching drum, the smallest values of boonness of fibrous material of long-fibred flax of Gladiator (a) and Esman (b) flax varieties were observed at scutching drum rotation speeds n = 300-360 min^{-1}.

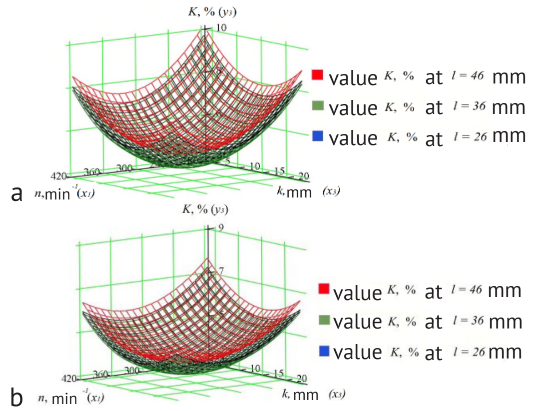

Figure 9. *Response surface of the dependence of output values of the boon content indicator, K, % (y_2) of raw flax of Gladiator (a) and Esman (b) varieties on the input factors considering the clearance between the grid and the scutching drum l, mm, in the second section of the proposed equipment*
Source: *developed by the authors*

According to the analysis of the response surfaces (Fig. 9) of the regression model y_2, it can be stated that during mechanical processing in the second section of the proposed equipment, at a scutching drum rotation speed n = 300 min^{-1} and dilution value k = 14 mm between the scutching knife and the batten bar of the scutching drum, the smallest values of boonness of fibrous material of long-fibred flax of Gladiator (a) and Esman (b) varieties were achieved at a dilution value l = 26-36 mm between the scutching drum and the grid of the scutching unit.

The analysis of the research results and response surfaces of regression models y_2 indicates that, under rotatable planning, the best results of mechanical processing of Gladiator and Esman flax fibrous material can be achieved at a dilution value k = 14-19 mm, a scutching drum rotation speed n = 300-360 min^{-1} and a dilution value l = 26-36 mm. The identified optimal parameters for mechanical processing in the second section of the experimental equipment provide rational values for achieving the smallest values of boonness of fibrous material. The study of the influence of these factors in the second section of the experimental equipment showed that their effect on the quantitative and qualitative characteristics of Gladiator and Esman flax fibers was consistent.

The mechanical processing of the Gladiator and Esman flax varieties was analysed through the constructed response surfaces of regression models for cleaning fibers from the boon and foreign impurities in the third section of the proposed equipment, as shown in Figures 10-12.

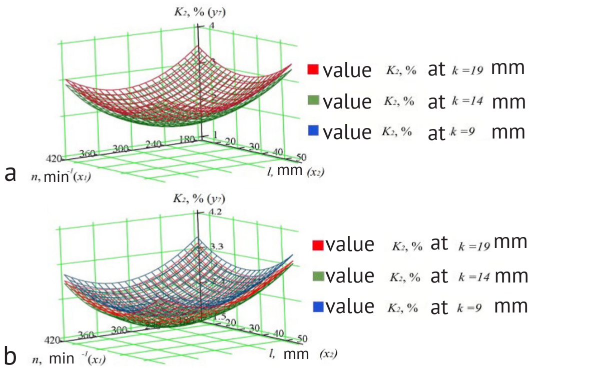

Figure 10. *Response surface of the dependence of output values of the boon content indicator K_2, % (y_3), in the fibrous mass of Gladiator (a) and Esman (b) flax varieties on the input factors considering the dilution value between the scutching knife and the batten bar of the scutching drum k, mm, in the third section of the proposed equipment*
Source: *developed by the authors*

The analysis of the response surfaces (Fig. 10) of the regression model y_3 demonstrated that at a scutching drum rotation speed $n = 300$ min^{-1} and dilution value $l = 36$ mm between the scutching drum and the grid of the scutching unit, the smallest values of boonness of fibrous material of long-fibred flax of Gladiator (a) and Esman (b) varieties during mechanical processing in the third section of the proposed equipment were observed, when the clearance between the scutching knife and the batten bar of the scutching drum was approximately $k = 14$ mm.

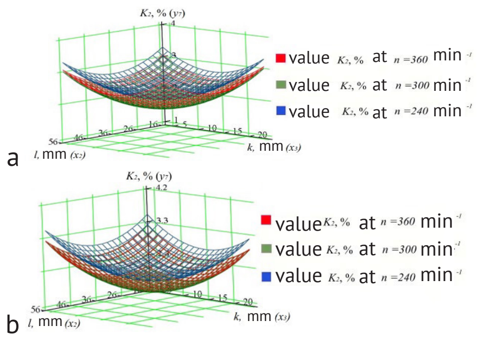

Figure 11. *Response surface of the dependence of output values of the woody core content indicator K_2, % (y_3), in the fibrous mass of Gladiator (a) and Esman (b) flax varieties on the input factors considering the rotation speed of the scutching drum n, min-1, in the third section of the proposed equipment*
Source: *developed by the authors*

The analysis of the response surfaces (Fig. 11) of the regression model y_3 indicated that during mechanical processing in the third section of the proposed equipment, at a dilution value $l = 36$ mm between the scutching drum and the grid of the scutching unit and a clearance *k = 14 mm* between the scutching knife and the batten bar of the scutching drum, the lowest boon content in the flax fibers of Gladiator (a) and Esman (b) varieties was achieved at a scutching drum rotation speed range $n = 300$-360 min^{-1}.

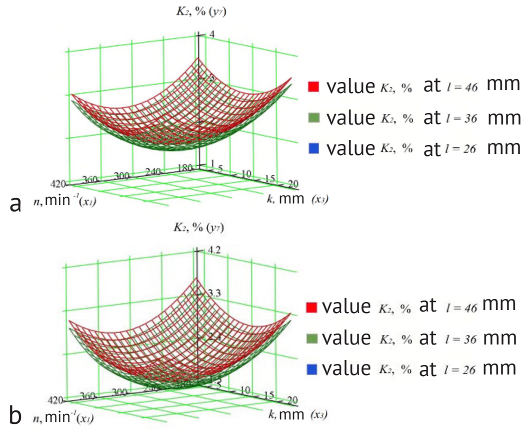

Figure 12. *Response surface of the dependence of output values of the boon content indicator K_2, % (y_3), in the fibrous mass of Gladiator (a) and Esman (b) flax varieties on the input factors considering the clearance between the grid and scutching drum l, mm, in the third section of the proposed equipment*
Source: *developed by the authors*

The analysis of the response surfaces (Fig. 12) of the regression model y_3 indicates that at a scutching drum rotation speed $n = 300$ min^{-1} and dilution value $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, the lowest values of boonness of fiber content in the flax fibers of Gladiator (a) and Esman (b) varieties were achieved, when the clearance between the scutching drum and the grid of the scutching unit was approximately $l = 36$ mm during mechanical processing in the third section of the proposed equipment.

The analysis of the research results and the response surfaces of the regression models y_3 showed that under optimal rotational planning, the best results of mechanical processing of Gladiator and Esman flax fibers could be achieved with a dilution value was approximately $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, a dilution value was approximately $l = 36$ mm between the scutching drum and the grid of the scutching unit, and a scutching drum rotation speed was approximately $n = 300$ min^{-1}. This was because increasing the rotation speed of the scutching drum leads to greater fiber damage, which was economically unfeasible for the final processing result. The optimal parameters for the mechanical processing of flax fiber in the third section of the proposed equipment would involve rational values that minimise the content of boonness in the raw fiber.

The study of the impact of the mentioned factors on the process of processing the stem material in the third section of the proposed equipment revealed that their effect on the quantitative and qualitative characteristics of Gladiator and Esman flax fibers were of the same character of action and passes for them unambiguously for both varieties.

The research results showed that by processing uniform flax stem material in the proposed method, it was possible to obtain the raw fiber in the crushing section at a specific pressure of 9.8 daN/cm in the pair of crushing rollers, with raw material moisture at 14%, and the normal degree of ripen trusts at 6 units, with a compress of trusts was approximately 25%. Under these conditions, crushing in the first section of the proposed equipment results in flax fiber with a boon content of 48-49%. It was also found that the most optimal conditions for mechanical processing of raw flax fiber in the second section of the proposed equipment with properly adjusted scutching unit parameters include a scutching drum rotation speed $n = 300$ min^{-1}, a dilution value $l = 36$ mm between the scutching drum and the grid of the scutching unit, and a dilution value $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, which allows obtaining a fibrous mass with foreign impurities at 3.5%.

Research of the third section of the proposed equipment showed that the most rational conditions for scutching flax fiber occur at a scutching drum rotation speed $n = 300$ min^{-1}, a dilution value $l = 36$ mm between the scutching drum and the grid of the scutching unit, and a dilution value $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, resulting in fiber with foreign impurities at a level of 1.86%.

The obtained research results suggested that the proposed method of processing flax stems and the developed equipment can be used in the production of natural, ecologically clean fiber, enabling manufacturers to produce fiber products with low levels of boon content, which can be of interest to both Ukrainian and foreign investors. Considering the current trends in consumer demand for "green" products, this could be an additional factor in spreading this innovative development in the processing sector of the light industry, as well as provide the national producer with the essential raw materials for making everyday products and those for military and special purposes.

Conclusions

A method of processing the trusts without dividing the fiber into long and short, which allows manufacturers to process the stalk material of flax and obtain fiber products of proper quality with a low boon content of about 1.86%, was proposed as a result of the study. The technological process for obtaining uniform fiber based on the innovative mechanical processing scheme for non-oriented flax stems involves the possibility of applying double scutching and shaking, with the need for these steps depending on the technical necessity and economic feasibility of completing the full processing cycle to obtain high-quality final products.

It is recommended to carry out processing of long-fibred flax trusts in the first part of the equipment at a specific pressure of 9.8 daN/cm in a pair of rolls, a raw material humidity 14%, a normal degree of ripen trusts at 6 units on the proposed equipment for obtaining high qualitative and quantitative characteristics of fibrous products. In the second and third sections, the processing should involve a scutching drum rotation speed $n = 300$ min^{-1}, a dilution value $l = 36$ mm between the scutching drum and the grid of the scutching unit, and a dilution value $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, which can be considered the most rational mode for processing the fibrous material.

The innovative technical and technological developments used in the study have made it possible to obtain flax fiber with low foreign impurity content, expanding its use in the textile, pulp and paper, furniture, construction, medical, and automotive industries, as well as in the production of items for military and special purposes, which are especially in demand in Ukraine.

The obtained research results indicated the possibility of widespread application of the proposed innovations in the production of natural fiber, as well as the need to explore the potential for processing other types of bast fiber raw materials on the proposed equipment. Further research should focus on detailed studies of other processing parameters and the characteristics of the fibrous product. Therefore, an important task for future research is the development of modern equipment or the modernisation of existing equipment to provide the industry with the capabilities to improve the qualitative and quantitative characteristics of natural fibers obtained from traditional bast fiber crops in Ukraine.

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Conflict of Interest

None.

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Дослідження виробництва волокна льону-довгунця за інноваційною технологією

Юрій Березовський

Доктор технічних наук, професор
Київський національний університет будівництва і архітектури
03037, просп. Повітряних сил України, 31, м. Київ, Україна
https://orcid.org/0000-0002-9645-2743

Тетяна Кузьміна

Доктор технічних наук, професор
Херсонський національний технічний університет
29016, вул. Інститутська, 11, м. Хмельницький, Україна
https://orcid.org/0000-0002-6113-1923

Наталя Ляліна

Доктор технічних наук, професор
Київський національний університет будівництва і архітектури
03037, просп. Повітряних сил України, 31, м. Київ, Україна
https://orcid.org/0000-0002-9364-0925

Галина Бойко

Кандидат технічних наук, доцент
Херсонський національний технічний університет
29016, вул. Інститутська, 11, м. Хмельницький, Україна
https://orcid.org/0000-0001-8773-5525

Тетяна Головенко

Доктор технічних наук, старший дослідник
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-1792-9364

Анотація. Сучасні потреби споживачів вимагають розширення асортименту екологічно чистої продукції, а також забезпечення української промисловості сировиною для виготовлення товарів воєнного та спеціального призначення. Це можна здійснити за допомогою українського виробництва волокнистої продукції з льону-довгунця з використанням нових технологій та інноваційних розробок. Метою роботи став пошук покращених виробничих умов переробки льону-довгунця та розробка способу переробки трести без розподілу волокна на довге та коротке для забезпечення національного виробника якісним волокнистим продуктом з можливістю розширених умов його використання. Для досягнення поставленої мети було проведено аналіз технічних і технологічних можливостей виробників волокнистої продукції, визначено попит споживачів на натуральне природне волокно, з'ясовано теоретичні підходи у вирішенні питань очищення волокнистого матеріалу. В умовах виробничого контролю дослідження якісних і кількісних характеристик волокнистого продукту здійснювалося за органолептичними та інструментальними методами оцінки. Під час проведення апріорного експерименту було визначено найбільш значимі фактори впливу, які мають найбільший вплив на проходження процесів проминання стебел та тіпання волокнистого сирцю льону-довгунця. Для визначення раціональних параметрів проходження процесу очищення волокнистого продукту з використанням програмного забезпечення та застосування регресійного аналізу шляхом здійснення моделювання технологічного процесу отримання однотипного волокна за розробленими інноваційними складовими, одержано регресійні моделі процесу знекостричення в різних частинах запропонованого обладнання. У роботі було з'ясовано умови використання запропонованого обладнання та вплив роботи різних частин устаткування на економічний результат переробки трести льону-довгунця, а також встановлено напрямки подальшого використання отриманого волокнистого продукту. Одержані результати досліджень можуть допомогти національному виробнику товарів повсякденного використання та спеціального і воєнного призначення вирішити проблему забезпечення якісною волокнистою сировиною, забезпечити підвищення конкурентоспроможності української продукції на внутрішньому та зовнішньому ринках товарів і послуг

Ключові слова: інновації; сировина; волокнистий продукт; м'яття; тіпання; якість; знекостричення