OPTIMIZATION OF THE DECORTICATION PROCESS OF INDUSTRIAL HEMP STEMS BY MATHEMATICAL PLANNING METHOD
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ОПТИМІЗАЦІЯ ТЕХНОЛОГІЧНОГО ПРОЦЕСУ ДЕКОРТИКАЦІЇ СТЕБЕЛ ТЕХНІЧНИХ КОНОПЕЛЬ МЕТОДОМ МАТЕМАТИЧНОГО ПЛАНУВАННЯ

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ABSTRACT

The paper presents the results of theoretical and experimental studies aimed at optimizing the decortication process of industrial hemp stems. In order to achieve this goal, physical and mechanical properties of industrial hemp straw stems were investigated, with the choice of the main quality indicator - diameter, which directly influences the bast output. Also, with the help of mathematical planning of the experiment, the optimal treatment mode for the stems of industrial hemp with clearing of wood of 5-6% was calculated.

РЕЗЮМЕ

Представлена робота містить результати теоретичних та експериментальних досліджень, спрямованих на оптимізацію процесів декортикації стебел соломи технічних конопель. Для досягнення поставленої мети проводили дослідження фізико-механічних властивостей стебел технічних конопель з вибором основного показника якості – діаметра, який безпосередньо впливає на вихід лубу, та проведенням математичного планування експерименту, який дозволив отримати оптимальні режими переробки стебел з очищенням лубу від костриці 5-6 %.

INTRODUCTION

Hemp is a highly productive agricultural crop, the cultivation and processing of which allows to obtain income that is ten times higher than the cost of its cultivation and processing. However, the cultivation and processing of industrial hemp is currently declining significantly in Ukraine *(Boyko G. A., et al., 2018)*. This is due to a number of reasons - lack of capacity for primary processing, outdated regulatory documentation for determining the quality of raw materials, and the lack of modern lean processes, which leads to obtaining low quality products.

The main stage in processing industrial hemp straw stems in the field is decortication, which results in the destruction of stem structure and the separation of bast. During decortication, the connections between the fibrous layer and the wood must be broken and, at the same time, the strength of the bast should be maintained when fully released from shives *(Boyko G. A., et al., 2017)*. Thus, the influence of physical and mechanical properties on the process of decortication plays an important role in the output of high-quality bast. Therefore, in order to regulate the decortication process itself and determine the optimum breaking parameters, it is necessary to examine in detail all the qualitative properties of straw to determine the basic quality indicators that directly affect the fibre output.

At present, obtaining high-quality bast from stems of industrial hemp on decortication machines is an urgent task for experts in the hemp industry in many European countries. Many foreign and domestic scientists devoted their scientific works to the problem of studying the influence of physical and mechanical characteristics of hemp stems on the operation modes of decorticators: *Hiliazetdinov R.N., Ipatov O.M., Novikov Ye.V., Hobson R.N., Amaduccis D.I., Igathinathane C.A., Kovur S.K., Munder F. (Boyko G. A., et al., 2017).*

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In these works, it is stated that the main parameters for establishing the optimal decortication mode are the roller set, the depth of the grooves, the pressure of the roller springs and the feed rate of the stems in the processing area.

Taking into account previous researches of physical and mechanical indicators of the stems of industrial hemp straw, in this paper the optimal parameters of the decortication mode and their influence on qualitative indicators of initial production were established by means of mathematical planning.

MATERIALS AND METHODS
Materials

For conducting the research, new varieties of industrial hemp have been selected, bred by the Institute of Bast Crops of NAASU and harvested at different maturity periods (green, full maturity), which are most often sown by agrarians in Ukraine: Viktoria, Gliana, and Nika.

Hemp fibre was obtained on a decorticator developed by «CannaSystems» (Canada). The modern decorticator simultaneously collects and processes the stems of industrial hemp, both on the field and in a stationary environment.

Raw material is fed to the unit through the front conveyor system. Straw is collected and fed by conveyor to the grinding rolls, and the wood is sent through the back holes to the second conveyor. As a result of this process, fibre is obtained with a purification of up to 8% in just one pass.

For the research on the industrial hemp stems a decorticator developed by CannaSystems was used. Currently, this technology is used in North American countries, China and Australia. According to this technology, the stems of hemp straw, after mowing in the field, come to the mobile decorticator, which in the process of processing the stems in the rollers are separated by the bast and wood, which are directed separately to different conveyor belts of the decorticator *(Boyko G. A., et al., 2017)*. This technology is shown in Figures 1, 2.
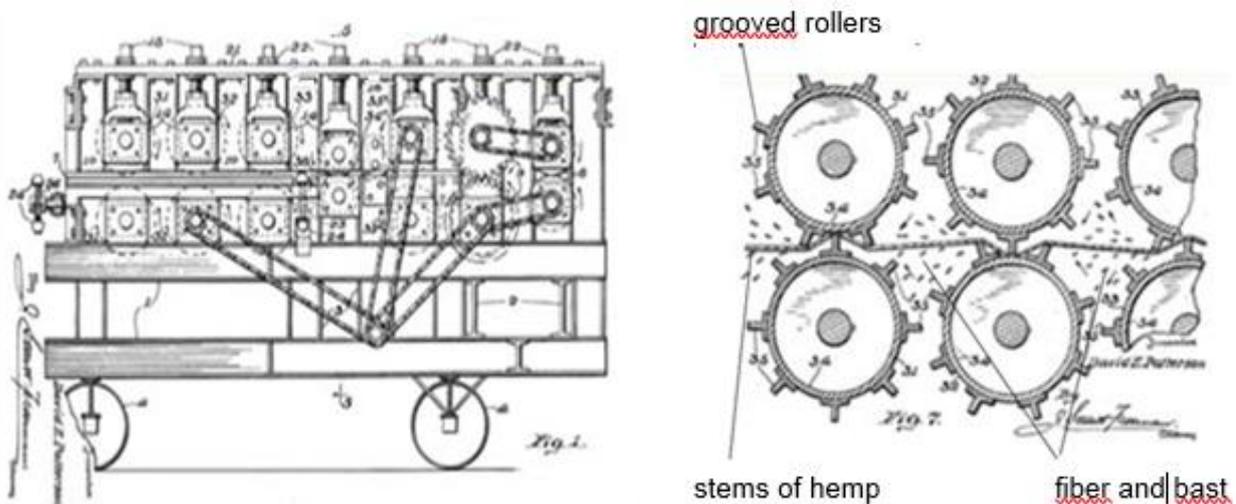
Fig. 1 - Decorticator for processing stems of hemp straw in the field and stationary conditions

Fig. 2 - Working elements of the decorticator
A - a pair of smooth rollers; B - three pairs of grooved rollers
C - decortication field; D - power rotor; E - the main fixed rotor

The main stage in the technological process of processing the stems of hemp straw in the field is decortication, which results in the destruction of the stem structure and the separation of the bast. During decortication, the bonding between the fibrous layer and the wood must be broken and, at the same time, the strength of the bark should be maintained when fully released from the wood.

The main working bodies of the decorticator are horizontal grooved rollers shown in Fig. 3.
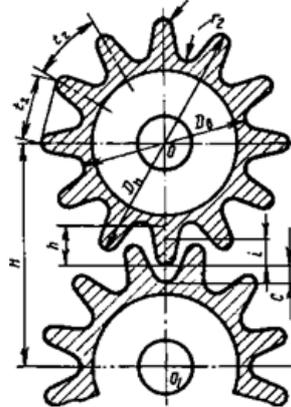
Fig. 3 - The main dimensions of the rollers in the decorticators

The decorticator, depending on the physical properties of hemp straw stems, changes the set of rollers, the depth of the grooves, the amount of pressure on the permeable material, the density of loading of the decorator raw material, the speed of rotation of the rollers and the location of the stems relative to the grooves.

When decorticating large diameter hemp stems, a set of small diameter rollers are used and, conversely, large diameter rollers are used to decorticate small diameter hemp stems.
To increase the efficiency of the passage of hemp straw stems increase the depth of the grooves. When it is necessary to soften the passage mode, which is important in the case of processing weakened and easily processed stems, the depth of the grooves must decrease.

Unit specifications:
- Processing speed: varies according to the feed rate of the wood from 2 t/h. up to 5 t/h.
- Hydraulic flow of 100-150 litres/min., liquid/cooling 30 hp.
- The basis of the unit is a power unit with a capacity of 15 hp, a feed conveyor 5 l.s.
- Conveyors weight 2000 kg, conveyor systems 5500 kg.
- Working surface 900 mm, length 1.8 m wide 2.43 m
- Conveyor length 3.65 m, height 2.74 m
- The unit is equipped with a rail and a cut-off switch for safety.
- The unit must be serviced by two people.
- Front and rear clearance for straw 3 m., 300 mm lateral clearance for collecting raw material / cleaning.
- The input tray is installed for fast straw feed systems.
- AC 220V motor, PTO14 hydraulic drive.
- It processes from 4,000 to 16,000 tons/year.

Methods

In order to ensure the validity of the conclusions based on the experimental data, the results of the experiments were statistically processed for the case of small samples from the general population with normal distribution *(Ternova T.I. et al., 2018).* The following statistical characteristics were determined: arithmetic mean; deviation from the arithmetic mean; variance; mean square deviation; coefficient of variation; the confidence interval in which the mean of the measurement results is likely; relative error; absolute error.

Selection of decortication parameters by rotatable design

In Ukraine, the stems of industrial hemp are processed generally by traditional technology - the technology of dry processing of wood. Traditional technologies are aimed only at obtaining the most valuable long parallelized hemp fibre - raw materials whose physical and mechanical properties are only able to satisfy the needs of twine and rope factories. The low percentage of long fibre hemp yield (15-20%) compared to its high content in stems (more than 35%) and a significant amount of fibrous waste

(approximately 75-80% by weight of recycled wood) is evidence of the imperfection of existing technologies of primary treatment of this bast hemp culture and the irrational use of hemp.

In order to obtain greater fibre yield and high quality, Kherson National Technical University scientists are constantly researching the improvement of both traditional and modern technologies for processing industrial hemp straw.

The scientists of Kherson National Technical University carried out a number of studies on the development of an effective decortication process for the processing of industrial hemp. Initially, to determine the optimum modes of decortication, the physical and mechanical characteristics of industrial hemp stems were investigated and the main input quality index of stems - diameter (x_1) was selected, which has the greatest influence on the process of their breaking in decorticators *(Tihosova A.A., et al., 2018).* The content of shives in the bast after breaking the stems (y) was selected as the output characteristic, which can be used to evaluate the quality of the separation of bast from hurds. The quality of breaking in the decorticator rollers depends mainly on the depth of the grooves (x_2).

Thus, on the basis of the obtained data, mathematical models of the process of industrial hemp stems decortication of different harvesting periods for all three studied varieties were obtained in order to produce bast suitable for widespread use, that is, as much as possible cleaned from shives *(Ternova T.I., et al., 2018).* Rotatable second-order experiment design optimized the setting of groove depth (x_2) depending on the diameter of industrial hemp stems (x_1) for three varieties - Gliana, Nika and Viktoria - to obtain bast with predetermined content values of shives (y) under different periods of harvesting. All indicators of the experimental calculations are shown in table 1.

Table 1

Matrices of rotatable design of the second-order experiment

Variety and harvesting period	Design Matrix of experiment	Diameter of stems, mm	Dependence of the shive content in the bast on the grooves depth and the diameter of hemp straw stems
Gliana (green harvesting of industrial hemp straw stems)	maximum diameter at $x_1 = +1$	7.4 mm	
	minimum diameter at $x_1 = -1$	5.8 mm	
	optimum grooves depth x_2	6.0 mm	
Nika (green harvesting of industrial hemp straw stems)	maximum diameter at $x_1 = +1$	9.3 mm	
	minimum diameter at $x_1 = -1$	7.7 mm	
	optimum grooves depth x_2	6.0 mm	
Viktoria (green harvesting of industrial hemp straw stems)	maximum diameter at $x_1 = +1$	8.1 mm	
	minimum diameter at $x_1 = -1$	6.5 mm	
	optimum grooves depth x_2	6.0 mm	

Variety and harvesting period	Design Matrix of experiment	Diameter of stems, mm	Dependence of the shive content in the bast on the grooves depth and the diameter of hemp straw stems
Gliana (harvesting for seeds upon full maturity of stems)	maximum diameter at $x_1 = +1$	7.8 mm	
	minimum diameter at $x_1 = -1$	6.2 mm	
	optimum grooves depth x_2	6.0 mm	
Nika (harvesting for seeds upon full maturity of stems)	maximum diameter at $x_1 = +1$	9.5 mm	
	minimum diameter at $x_1 = -1$	7.9 mm	
	optimum grooves depth x_2	6.0 mm	
Віктоrіа (harvesting for seeds upon full maturity of stems)	maximum diameter at $x_1 = +1$	9.8 mm	
	minimum diameter at $x_1 = -1$	8.2 mm	
	optimum grooves depth x_2	6.0 mm	

The mathematical models of the process of industrial hemp stems decortication of different harvesting periods for all three studied varieties were obtained in order to produce bast suitable for widespread use, that is, as much as possible cleaned from shives. Thus, as a result of a full factorial experiment, the dependence of the quality of decortication of hemp stems of three varieties - Gliana, Nika, Viktoria - on the depth of the grooves of decorticator rolls and the diameter of the stems after green harvesting and harvesting for seeds upon full maturity was obtained.

Determination of coefficients and absolute errors

In further studies of rotatable experiment design, using known ratios to obtain the coefficients of equation, the coefficients for the three studied varieties and two harvesting periods were determined, that is, for six dependencies, as well as absolute errors in calculating their values *(Ternova T.I., et al., 2016)*. The calculated dependence coefficients and the values of their absolute errors are given in Table. 2.

Table 2

Dependence coefficients and the values of their absolute errors

i	y_1 Gliana, full maturity		y_2 Nika, full maturity		y_3 Viktoria, full maturity		y_4 Gliana, green harvesting		y_5 Nika, green harvesting		y_6 Viktoria, green harvesting	
	b_i	Δb_i	b_i	Δb_i	b_i	Δb_i	b_i	Δb_i	b_i	Δb_i	b_i	Δb_i
0	11.96	0.53	12.50	0.34	13.96	0.36	10.16	0.19	11.46	0.27	10.98	0.15
1	2.68	0.42	2.70	0.27	2.88	0.28	2.82	0.15	2.70	0.22	2.11	0.12
2	-5.53	0.42	-5.82	0.27	-6.26	0.28	-5.24	0.15	-5.71	0.22	-5.92	0.12
12	-0.35	0.59	-0.58	0.38	0.21	0.40	-0.53	0.21	-0.45	0.31	0.70	0.16
11	0.13	0.45	0.15	0.29	0.35	0.30	0.12	0.16	0.12	0.23	0.06	0.13
22	0.55	0.45	0.75	0.29	1.70	0.30	1.02	0.16	0.92	0.23	2.11	0.13

The adequacy of the obtained models was determined according to the Fisher criterion. For the 95% confidence probability, the number of degrees of freedom of the greater variance - 3 and less – 4, the critical value of the Fisher criterion is $F_{cr.} = 6.59$. The values of the Fisher criterion, which were determined in the study of each of the designed models, are shown in table 2. It is obvious that all $F_{observatin.} < F_{cr.}$, therefore designed models are adequate (table 3).The significance of the coefficients of each model was estimated by the magnitude of their errors, the values of which are given in Table 2. As it is known, if the absolute value of the coefficient is less than the value of its absolute error, such coefficient is considered insignificant and can be excluded from the equation.

Table 3

Determining the Fisher criterion value $F_{observatio}$ for the dependencies $y_1 – y_6$

y_1	y_2	y_3	y_4	y_5	y_6
6.075	5.981	6.580	4.578	6.198	5.687

According to the experimental data, the following analytical dependencies were eventually obtained (1-6):

$$y_1 = 11.96 + 2.68x_1 - 5.53x_2 + 0.55x_2^2, \tag{1}$$

$$y_2 = 12.50 + 2.70x_1 - 5.82x_2 - 0.58x_1x_2 + 0.75x_2^2, \tag{2}$$

$$y_3 = 13.96 + 2.88x_1 - 6.26x_2 + 0.35x_1^2 + 1.70x_2^2, \tag{3}$$

$$y_4 = 10.16 + 2.82x_1 - 5.24x_2 - 0.53x_1x_2 + 1.02x_2^2, \tag{4}$$

$$y_5 = 11.46 + 2.70x_1 - 5.71x_2 - 0.45x_1x_2 + 0.92x_2^2, \tag{5}$$

$$y_6 = 10.98 + 2.11x_1 - 5.92x_2 + 0.70x_1x_2 + 2.11x_2^2. \tag{6}$$

The obtained analytical dependences were used in the paper to determine the influence of the diameter of industrial hemp straw stems of different varieties on the quality of bast cleaning from shives in the process of decortication.

RESULTS AND DISCUSSION

According to the results of the tests, the mathematical dependences of the wood content in the fiber on the diameter of the hemp straw stalks and the mathematical dependences of the wood content in the fiber on the depth of the grooves of the decorator rollers were obtained.

According to the experimental design matrices shown in Table 1, the stems of industrial hemp straw of three varieties - Gliana, Nika, Viktoria - were decorticated after green harvesting and harvesting upon full maturity. As a result of processing the experimental data, mathematical dependences of the shives content in the bast on the diameter of hemp straw stems were obtained, and the mathematical dependences of the shives content in the bast on the depth of the decorticator rollers' grooves, which are presented in Table 4.

**Mathematical dependences of the shives content in the bast on the depth
of the decorticator rollers' grooves**

Harvesting technology	yg1, yn1, yv1 – shives content in bast depending on the influence of basic indicators of the decortication of hemp straw stems under green harvesting (g -Gliana, n – Nika, v – Viktoria)	Graphical representation of the dependencies: 1-Gliana, 2- Nika, 3- Viktoria.	The highest degree of bast cleaning, depending on the optimal modes, %
	The influence of diameter on the quality of bast cleaning		
Green harvesting technology	$y_{g1} = -12.97 + 2.87d$ $y_{n1} = -17.21 + 2.81d$ $y_{v1} = -18.77 + 3.50d$		4,5-6,0
Full stem maturity	$y_{g2} = -16.43 - 3.35d$ $y_{n2} = -17.01 + 2.81d$ $y_{v2} = 21.00 - 6.18d + 0.54d^2$		5,0-6,5
	The influence of grooves depth on the quality of bast cleaning		
Green harvesting technology	$y_{g3} = 61.76 - 15.41h + 1.02h^2$ $y_{n3} = 63.06 - 14.93h + 0.92h^2$ $y_{v3} = 93.05 - 27.04h + 2.11h^2$		4,0-5,0
Full stem maturity	$y_{g4} = 53.48 - 11.07h + 0.55h^2$ $y_{n4} = 60.27 - 13.28h + 0.75h^2$ $y_{v4} = 87.72 - 23.24h + 1.70h^2$		5,5-7,0

Analyzing the data from table 4, it can be noted that the thinner the stems of industrial hemp straw, the lower the content of shives in the bast after the processing of stems on the decorticator at the optimum depth of the grooves *(Ternova T.I., 2018)*. Also, it should be noted that at the optimum depth of the grooves in the bast of Victoria hemp variety, the content of shives is 9.41% at an average diameter of 9.0 mm, and the lowest content of shives is 6.98% which is characteristic of the bast of Gliana hemp variety with an average diameter of 7.0 mm.

In view of the above, in order to obtain high quality raw materials, it is necessary to regulate the parameters of decorticator adjustment depending on the diameter of stems and the hemp harvesting period, taking into account their varietal differences.

Nika, Gliana and Victoria varieties can be processed using all existing industrial hemp processing technologies. The results of fibre output and wood cleaning may be different. But at this stage of work, the optimal technology of processing stems of industrial hemp of these varieties for Ukraine was selected.

CannaSystems' decorticator processes hemp stems on the field, which saves on the cost of additional space. But the quality indicators of fibre in their parameters satisfy the domestic entrepreneurs with the further processing of the obtained fibre.

CONCLUSIONS

The analysis of regression models and graphical dependences of the quality indicators of bast quality on the harvesting period of industrial hemp straw stems of different varieties showed that hemp stems upon full maturity require more intensive actions during the processing on the decorticator to clean bast from shives than the hemp stems of green harvesting *(Boyko G. A., et al., 2019)*. Also, the direct dependence of the output of high-quality raw material on the diameter of stems of industrial hemp straw was proved. Thus, for better bast cleaning from shives when decorticating hemp stems, the grooves depth should be set up depending on the diameter of stems, the harvesting period and the varietal differences of hemp.

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