UDC 633.522
DOI: 10.15587/1729-4061.2024.315058

DEFINING PATTERNS IN THE INTENSIFICATION OF HEMP STALK RETTING PROCESSES

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The object of this study is the technological operations of primary hemp stalk processing, factors that intensify the retting process, and stalk crushing.

The task addressed was the identification of technical and technological solutions that would enable intensification of the production processes for hemp retting.

Based on the research results, it was established that placing the flattened stems in natural and polypropylene bags, compared to cellophane bags, accelerates the preparation time of retted stalks in a vertical position by 1.19 times, and in a horizontal position by 1.38 times. The retting time for horizontally placed crushed stalks with weekly moistening twice a week is 2.16 times shorter than for uncrushed ones.

It was determined that the process of crushing pre-prepared and cured stalks, whether in a vertical or horizontal position, allows for a significant reduction in retting period by 2.14 times, and for freshly cut stalks – by 1.27 times.

The intensity of the reflected light flux changed in the case of reaching the retting phase for unflattened stems with their vertical placement from the initial 32.0 lux to 18.0 lux. In flattened stems under the conditions of their vertical placement – from 50.7 to 16.3 lux, respectively. In the case of horizontally placed crushed stalks, the light intensity at the retting phase was 20.3 lux.

The lowest fiber breaking load value of 5.0 daN was established for the retted stalks obtained from freshly cut flattened stems in a vertical position, as well as in non-flattened stems in the vertical (7.0 daN) and horizontal (3.5 daN) positions

Keywords: industrial hemp, harvesting technologies, retting, preparation time, fiber quality

Received 02.09.2024
Received in revised form 28.10.2024
Accepted 11.11.2024
Published 20.12.2024

How to Cite: *Sheichenko, V., Rogovskii, I., Skoriak, Y., Petrachenko, D., Shevchuk, M., Sheichenko, D., Titova, L., Sivak, I. (2024). Defining patterns in the intensification of hemp stalk retting processes. Eastern-European Journal of Enterprise Technologies, 6 (1 (132)), 50–63. https://doi.org/10.15587/1729-4061.2024.315058*

1. Introduction

The search for ways to increase the efficiency of the production of industrial hemp, as a crop with extremely high consumer potential, is an important and relevant area of scientific research. The development and implementation of new technical and technological solutions are aimed at improving the quality of products, reducing energy consumption for their production, and expanding the range of products. The above predetermines the increased requirements for the management of technological processes in the preparation of retted stalks, the search for alternative solutions, non-standard approaches that make it possible to intensify biological processes and shorten the term of retting.

It is well known that the unevenness of the laying of retted stalks in terms of the length and thickness of the layer is the main factor on which the output of the fiber depends in the process of retting. The unevenness in the bedding of retted stalks is a function of the thickness of the spreading layer. The stretching of the stems, the terms of spreading and retting exert a significant influence on the quality of the fiber [1, 2].

It should be noted that the best in terms of technological and operational properties are fibers from the retted stalks prepared by water soaking and steaming [2]. The method of water soaking is used to obtain high-quality fibers, especially for thin textile products. Water soaking involves soaking the stalks, resulting in high quality fiber that is difficult to achieve by other methods [3].

The method of steaming for the preparation of hemp retted stalks is given in [4]. Fibers obtained from such retted stalks have high strength, which makes them suitable for the manufacture of twisted products. Such methods contribute to the improvement of the quality of fibers, increase the breaking load and flexibility, which makes it possible to obtain fiber with better properties.

Work [5] outlines the main indicators by which the quality of fibers is evaluated. These include breaking load, linear density, and percentage yield of long fiber. However, their high material and economic cost, as well as a significant share of manual labor costs, are among the disadvantages of the above methods for preparing retted stalks.

That is why the substantiation of factors intensifying the processes of hemp retting is an urgent scientific and practical task; solving it could make it possible to significantly increase the efficiency of hemp farming.

2. Literature review and problem statement

Technical hemp is characterized by two periods of maturity. Harvesting of hemp is possible in two periods – for fiber (greens) and seeds and fiber (bilateral use) [6]. The choice of the harvesting technology option is determined by the farm's strategy and determined by established priorities. However, the timeliness of the organization of harvesting operations is considered one of the key factors that determine the quality of products and the profitability of crop cultivation. The limitation of technical resources leads to a violation of rational collection terms and product losses.

Green hemp crops are harvested according to classic technologies, which are aimed at obtaining the maximum amount of long fiber. Green crops begin to be harvested during the period of 10–50 % seed maturation, when the formation of the crop and fiber quality is completed [7]. Under the specified conditions, potentially high-quality raw materials are obtained. Work [8] lists the limitations of the use of conventional technologies. The specified restrictions relate to the specificity of the use of narrow-profile, special hemp-harvesting equipment. The high cost of special machines, their low productivity, small annual loading along with significant human resources make such technologies unsuitable for widespread use. The development of universal harvesting technologies is a direction of increasing the efficiency of crop production. Under such conditions, high fiber quality indicators are achieved thanks to the use of modern technical means that are adapted to the technology.

In work [4], it is noted that the highest yield of seeds, straw, and fiber with two-way use is made possible by harvesting monoecious hemp during the ripening period of 75 % of the seeds in most plants. Earlier harvesting is impractical as it leads to a shortage of 18–54 % of the seed crop, and a delay in harvesting increases its losses to 24–61 %. However, issues regarding increasing harvesting efficiency without loss of crop quality remained unresolved. After all, the main disadvantage of bilateral harvesting is the use of general-purpose agricultural machinery. This requires prior fine-tuning and modernization of individual units. Otherwise, the loss of part of the harvest and the deterioration of the quality of raw materials cannot be avoided.

Work [9] reports the results of research into the modern conditions of harvesting hemp for two-way use. It is noted that the main products (seeds and fibrous raw materials) are separated into several stages. At the first stage, the seed component of the crop is collected using combine harvesters. Preference is given to models with a higher lifting height of the harvester and a key type of straw shaker. Special attention is paid to monitoring seed damage and preventing straw from winding on the working bodies of the harvester. However, in the absence of special equipment, harvesting the stem part of the hemp crop remains unresolved. It was noted [10] that technological regulations provide for the use of machines and tools of general purpose: mowers, rakes, rollers, balers, etc. However, the factors of the intensification of the terms of preparation of retted stalks have not been considered or given. Among other things, it is not possible to use the full potential of the plants of the specified harvesting technology. This leads to a significant decrease in the overall efficiency of the process. One of the promising options for overcoming these obstacles is the development and implementation of new technical and technological solutions that will make it possible to optimize the harvesting process of the entire hemp crop.

Work [11] reports the results of studies on the primary processing of hemp, which include two main production cycles: the preparation of hemp and the processing of hemp into fiber. Depending on the mechanisms of destruction of connections between fibers and tissues in the stem of the plant, the methods of preparing retted stalks are divided into biological, chemical, and physical-chemical. In [12], it was noted that the most widespread method of primary processing of hemp involves extracting fiber from straw, previously transformed into retted stalks by means of biological soaking. However, the issues related to increasing the effectiveness of the methods for preparing the pulp to achieve the maximum fiber quality remain unsolved. The reason for this may be objective difficulties caused by the destruction of pectin substances connecting the fibers to the stem. The use of chemicals and special equipment leads to an increase in costs [5]. Microorganisms (bacteria, fungi) play a decisive role in the biological method. They produce enzymes that contribute to the destruction of pectin substances. This process enables the maximum extraction of fiber, which is the most valuable for industrial and economic use [13]. However, methods for intensifying the terms of retting are not given in the article.

Cold water and warm water soaking remain the most common techniques for making hemp retted stalks [14]. In work [15], it was noted that retting by spreading straw on laying spreads, as it is done to obtain flax retted stalks, is characterized by the deterioration of the fiber quality indicators from shale retted stalks. In particular, the yield of long fiber by the shale method is only 66 % compared to 75 % by the soaking method. The average number of the long fiber is also lower – 5.2 vs. 6.6, and the short – 1.7 vs. 2.0, respectively. In addition, the retted stalks obtained by the shale method has a lower development number – 0.7 versus 0.9. An option to overcome these difficulties may be to improve the laying processes and introduce new approaches to processing the retted stalks.

Chemical and physical-chemical retting techniques are discussed in [16, 17]. The chemical technique involves the use of chemicals to break the bonds between the fiber and the wood in the hemp stems. However, significant financial costs for chemical preparations and the need for additional treatment facilities prevent the widespread use of this method. The physicochemical retting method, which includes thermochemical hydrolysis with the use of steam and high temperatures, also remains insufficiently widespread because of the high cost of implementation.

It should be noted that the method of dew moistening of stems remains the most economically beneficial. This method does not require additional resources and sophisticated equipment. It eliminates the need for the construction of treatment facilities, and the number of workers involved can be reduced to a minimum. However, the issue of improving fiber quality requires further research.

Work [18] reports the results of research into the process of hemp retting. The specified process needs further improvement, especially taking into account modern technological approaches. Questions caused by the impact of the latest technological solutions aimed at energy saving and increasing the efficiency of all stages of production and processing of biological crops remain unresolved.

Belt technologies for harvesting and transporting hemp stems look promising [19]. These technologies make it possible to create favorable conditions for the control over the process of roll formation of hemp stalks. They increase the level of manageability of production systems due to the compact placement of the crop on specially prepared areas of the field. This enables the step-by-step processing of the entire potential volume of hemp harvest.

Crushing of stems, as a method of intensification of biological processes at the stages of retting, is known and well studied [19]. However, the issues of systematic study of a set of factors that can significantly reduce the time of retting have remained out of the attention of researchers.

It is worth noting that changes in weather and climate conditions under which the modern development of agriculture takes place require more attention from scientists. Lack of moisture and other climatic factors lead to significant crop losses. Under such conditions, traditional approaches to growing and processing hemp do not always provide the expected results. That is why it is expedient to carry out comprehensive studies, which will take into account changes in weather and climate conditions and assess their impact on the processes of retting in different natural and climatic zones of hemp cultivation. Further research is necessary to devise adapted methods for preparing retted stalks that can function effectively under modern conditions. This could improve production efficiency and reduce the negative effects of natural and climatic factors on the process of growing and processing hemp.

3. The aim and objectives of the study

The purpose of our research is to improve the efficiency of hemp production by defining patterns to intensify the processes of hemp retting. This will make it possible to improve the quality of the product, ensure the rational use of modern harvesting and processing technologies.

To achieve the goal, the following research tasks were set:

– to establish the influence of packing (polypropylene burlap, natural burlap, cellophane) on the time of retting and fiber quality indicators;

– to determine the influence of the destruction of hemp stems by flattening on the time of retting and indicators of the quality of long fiber;

– to establish the influence of the condition (vertical, horizontal placement of the package) on the timing of retting and fiber quality indicators;

– to establish the quality indicators of the produced fiber.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our research is technological processes, stems of industrial hemp, as well as factors affecting the intensification of the retting process.

Our hypothesis assumes that there are such technical and technological solutions (type of packaging, arrangement of stems, mechanical actions on stems, moistening), the application of which could make it possible to reduce the time of hemp retting while preserving fiber quality.

Accepted assumptions:

– weather and climate conditions do not have a significant impact on the retting process. The research was carried out under controlled conditions with predefined humidity;

– chemical reactions between stems and packaging material do not occur;

– microbiological activity during the laying process of retted stalks was activated and regulated exclusively by external conditions (moistening and flattening).

Adopted simplifications:

– the impact of each factor was evaluated independently. Research was based on the assumption that changing one factor did not affect the action of others;

– mechanical flattening was carried out under the same conditions for all stems. The difference in the degree of flattening of the stem samples was not taken into account;

– the quality of the fiber was determined by the intensity of the reflected light flux and breaking load.

4. 2. Procedure for determining the impact of packing on the terms of retting

In 2023–2024, stems of industrial hemp were used as raw materials. The stalks were cut with a ZK-1.9 harvester in the ripeness phase of 66 % seed maturation and threshed with an MLK-4.5 thresher. The threshed stems were dried in the field. Dried stems were arranged in bundles for further research.

As factors intensifying the retting process, we examined the influence of:

– package (polypropylene burlap, natural burlap, cellophane);

– mechanical actions (flattening, rolling);

– state (vertical, horizontal placement of the package);

– moistening (treatment of stems every 7 days), as well as additional moistening (once a week during the laying period).

The research program provided for the assessment of the following indicators:

– characterization of stem in the field (input data);

– the degree of curing;

– the term of curing.

Sampling was carried out every 7 days and organoleptic criteria were used to evaluate changes in the color of the surface covering of the stem and the separation of the fibrous part from the wood. At the same time, the indicators of reflected light flux from the surface of the stem and strength (breaking load) were determined by the instrumental method.

According to the regulations of operations, the following procedures were carried out once a week. Stems were removed from each package; their color, condition, and the intensity of the reflected light flux were determined by the device. The established indicators were recorded in the journal. After the measurements, the stems were moistened by dipping them in a container with water. In experiments 2A and 2B, dipping the stems in a container with water was carried out twice a week.

Table 1 gives a schematic representation of the experimental part.

The characteristics of the raw material (hemp stems) before starting experiments on curing the retted stalks are given in Table 2.

It should be noted that the organoleptic evaluation of cured hemp stems by color and separation of fiber from wood was carried out simultaneously with the instrumental evaluation (by the intensity of the reflected light flux from the examined surface).

The experiments indicated in Table 1 had started on 02.10.2023 (on the 25th day after mowing).

The first selection with the determination of the condition of the stems in the experiments was carried out on the fourth day (October 5, 2023 – day 0 of measurement). After that, the following samples were taken every 7 days. The last measurement point is 77 days. Under these conditions, the color and condition of the stems were determined, as well as indicators of the intensity of the reflected light flux according to the device.

The following materials were used to determine the influence of the type of package: polypropylene burlap, natural burlap, cellophane bag (Fig. 1). Freshly cut not flattened, freshly cut flattened, dry not flattened, dry flattened stems were placed in the specified packages.

Table 1

Schematic representation of the retting curing process

In an upright position		In a horizontal condition	
Not flattened (A)	Flattened (B)	Not flattened (A)	Flattened (B)
Natural bag (b_n) – 1A-b_n	Natural bag (b_n) – 1B-b_n	Natural bag (b_n) – 2A-b_n	Natural bag (b_n) – 2B-b_n
Polypropylene bag (b_p) – 1A-b_p	Polypropylene bag (b_p) – 1B-b_p	Polypropylene bag (b_p) – 2A-b_p	Polypropylene bag (b_p) – 2B-b_p
Cellophane bag (b_c) – 1A-b_c	Cellophane bag (b_c) – 1B-b_c	Cellophane bag (b_c) – 2A-b_c	Cellophane bag (b_c) – 2B-b_c
Freshly cut, polypropylene bag (b_n) – 1A-b_{nfc}	Freshly cut, polypropylene bag (b_n) – 1B-b_{nfc}	Freshly cut, polypropylene bag (b_n) – 1B-b_{nfc}	Freshly cut, polypropylene bag (b_n) – 2B-b_{nfc}
–	–	Natural bag, water treatment 2 times – 2A	Natural bag, water treatment 2 times – 2B

Note:
1. *1A-b_n – vertical position, not flattened, natural bag.*
2. *1A-b_p – vertical position, not flattened, polypropylene bag.*
3. *1A-b_c – vertical position, not flattened, cellophane bag without processing.*
4. *1A-b_{nfc} – vertical position, not flattened, the bag is natural, the stems are freshly cut.*
5. *1B-b_n – vertical position, not flattened, natural bag.*
6. *1B-b_p – vertical position, not flattened, polypropylene bag.*
7. *1B-b_c – vertical position, not flattened, cellophane bag without processing.*
8. *1B-b_{nfc} – vertical position, not flattened, bag natural, stems freshly cut.*
9. *2A-b_n – horizontal position, not flattened, the bag is natural.*
10. *2A-b_p – horizontal position, not flattened, polypropylene bag.*
11. *2A-b_c – horizontal position, not flattened, cellophane bag without processing.*
12. *2A-b_{nfc} – horizontal position, not flattened, bag natural, stems freshly cut.*
13. *2B-b_n – horizontal position, not flattened, natural bag.*
14. *2B-b_p – horizontal position, not flattened, polypropylene bag.*
15. *2B-b_c – horizontal position, not flattened, cellophane bag without processing.*
16. *2B-b_{nfc} – horizontal position, not flattened, bag natural, stems freshly cut.*
17. *2A – horizontal position, not flattened, natural bag, treated with water 2 times.*
18. *2B – horizontal position, flattened, natural bag, treated with water 2 times.*

Table 2

The initial characteristics of the raw material (hemp stems) before starting the experiment on curing the retted stalks

Date of evaluation measurements	Stems	Organoleptic assessment of cured hemp stems by color and separation of fiber from wood	Instrumental estimation (by the intensity of the reflected light flux from the examined surface), lux
28.09.2023	Freshly cut not flattened	The color is yellow-green, straw, there is no separation	50.3
28.09.2023	Freshly cut flattened	The color is yellow-green, straw, there is no separation	43.3
28.09.2023	Dry not flattened	The color is yellow-green, straw, there is no separation	47.0
28.09.2023	Dry flattened	The color is yellow-green with a slight translucency of lighter fescue, straw, no separation	56.7

Fig. 1. Hemp stalks in packages of various types

The first selection with determination of the state of stems in the experiments was carried out on the fourth day (October 5, 2023 – day 0 of measurement). After that, the following samples were taken every 7 days. Under these conditions, the color and condition of the stems were determined, as well as indicators of the intensity of the reflected light flux according to the device. The organoleptic evaluation of cured hemp stalks by color and separation of fiber from wood was carried out simultaneously with the instrumental evaluation (by the intensity of the reflected light flux from the examined surface).

Statistical treatment of data was carried out using the analysis of variance ANOVA in the Microsoft Excel software. This made it possible to determine statistically significant differences between the studied groups. The main indicators of variance analysis were calculated: sum of squares (*SS*), degrees of freedom (*df*), mean square (*MS*), *F*-statistics, and significance level (*p*-value). The sum of squares reflects the total variability between groups, and the degrees of freedom provided a correct estimate of this variability. The mean square of the between-group variation made it possible to calculate the mean difference between groups, and the value of the *F*-statistic made it possible to estimate the relative variability of boundaries and within groups. The level of significance (*p*-value) testified to the probability that the observed differences between groups were not due to chance, and a value of $p<0.05$ confirmed a statistically significant difference between them.

4. 3. Procedure for determining the impact of mechanical actions (flattening) on the terms of retting

Freshly cut and dry hemp stems were flattened in a laboratory setup. The specified laboratory installation contained two spring-loaded rollers, the drive of the leading rollers of which was carried out manually. The gap between the rollers and the flattening force were the same for all the studied stems.

Non-flattened stems were used as controls. A schematic representation of the retting process is given in Table 1.

Organoleptic assessment of cured hemp stalks by color and separation of fiber from wood was carried out simultaneously with instrumental assessment (by the intensity of the reflected light flux from the examined surface).

4. 4. Methodology for determining the influence of the placing condition of package with stems (vertical, horizontal) on the timing of retting

The research program provided for vertical and horizontal placement of flattened and unflattened stems in packages made of woven polypropylene burlap, natural woven burlap, and cellophane bags (Table 1). In addition to the above experiments, flattened and non-flattened stems were placed in a horizontal position in bags made of natural burlap under the conditions of their moistening twice a week.

4. 5. Methodology for determining the quantitative and qualitative indicators of the produced fiber

According to the regulations of operations, the following procedures were carried out once a week. Stems were removed from each package; their color, condition, and the intensity of the reflected light flux were determined by the device. The established indicators were recorded in the journal. After the measurements, the stems were moistened by dipping them in a container with water. In experiments 2A and 2B (Table 1), the stems were immersed in a container with water twice a week.

The color change of the surface covering of the stem and the separation of the fibrous part from the wood were determined every 7 days. Indicators of reflected light flux from the surface of the stem and strength (breaking load) were determined by the instrumental method.

The indicator of fiber separation, both by the organoleptic method and by the device, was determined in different parts of the stem. Having carried out three repetitions of research, the average value was determined, which was entered in the table.

The assessment of quality indicators was carried out in accordance with the provisions of current regulatory and technical documents.

5. Results of investigating the influence of intensifying factors on the process of retting and fiber quality

5. 1. Results of determining the impact of packaging on the timing of retting

Table 3 gives dates of sampling for each variant of the experiment, from placing straw in packages to the readiness of the retted stalks.

Analyzing the results in Table 3, one should note the different number of samplings of research options before the readiness of the retted stalks. The fastest (30 days after starting the experiment) retted stalks were prepared in versions 2B-b_p (stems in a horizontal position, flattened, polypropylene bag) and 2B (stems in a horizontal position, flattened, a natural bag, moistened with water twice a week).

After 37 days, the retted stalks were prepared in the variants 1B-b_p (stems in a vertical position, flattened, polypropylene bag), 1B-b_p (stems in a vertical position, flattened, natural bag), and 2B-b_n (stems in a horizontal position, flattened, natural bag).

After 44 days, the retted stalks were prepared in the 1B-b_c version (stems in a vertical position, flattened, cellophane bag).

After 51 days, the retted stalks were prepared in versions 1A-b_c, 1B-b_{nfc}, 2B-b_c and 2B-b_{nfc}.

After 58 days, no detected samples (variants) of retted stalks were found.

After 65 days, the retted stalks were prepared in thever-sions 1A-b_{nfc}, 2A-b_c, 2A-b_{nfc} and 2A.

After 72 days, we discovered no samples (variants) of the prepared retted stalks.

After 79 days, in none of the options was the readiness of the retted stalks established.

Table 4 gives the results of statistical processing of the acquired data to determine the impact of packaging on the timing of retting.

It should be noted that the obtained data (Table 3) confirm the real and not random nature of the difference between the groups and testify to their statistically significant differences.

Retted stalks in variants 1A-b_n, 1A-b_p, 2A-b_n were selected coarse, not cured at a low temperature of preparation. The retted stalks in the 2A-b_p variant (stems in a horizontal state, not flattened, polypropylene bag) were selected slightly uncured.

Let's note the factors that intensified the process of preparing hemp retted stalks:

– mechanical influence – not flattened, flattened, rolling;

– placement on the soil surface – horizontally relative to the soil (on the surface), in a vertical position;

– packaging material – natural bag, polypropylene bag, cellophane bag;

– the state of the stem – freshly cut, dry;

– moisturizing – moisturized once a week, moisturized twice a week.

It was noted that the shortest period of retting (30 days) was established in two experiments (Table 2). Horizontally placed flattened stems, a natural bag with moisture twice a week. And the stems are flattened, horizontally located on the surface in a polypropylene bag. In the above variants, the common feature was the horizontal arrangement of the stems and their preliminary flattening (Fig. 2).

The term of preparation of retted stalks from the second group (37 days) is 23.3 % longer than the term of the first, the third (44 days) – by 46.6 %, the fourth (51 days) – by 70 %, the fifth (65 days) – by 116.6 %, respectively. It is worth noting that the common factor in all variants of experiments, where the readiness of the retted stalks was not reached in 79 days, was the absence of flattening. That makes it possible to draw a conclusion about the robustness of the process of flattening the stems under the conditions for determining the methods for intensification of the microbiological processes of transforming hemp straw into retted stalks.

Table 3

Dates and number of selections of each variant of the experiment, from placing hemp stalks with straw in the packages until the retted stalks are ready

Experiment variant codes		Selection dates	Number of selections to retting readiness, units
1	1A-b_n	5.10; 12.10; 19.10; 26.10; 2.11; 9.11; 16.11; 23.11; 30.11; 7.12; 14.12; 21.12.2023	12
2	1A-b_p	selections are similar to 1A-b_n	12
3	1A-b_c	5.10; 12.10; 19.10; 26.10; 2.11; 9.11; 16.11; 23.11.2023	8
4	1A-b_{nfc}	5.10; 12.10; 19.10; 26.10; 2.11; 9.11; 16.11; 23.11; 30.11; 7.12.2023	10
5	1B-b_n	5.10; 12.10; 19.10; 26.10; 2.11; 9.11.2023	6
6	1B-b_p	5.10; 12.10; 19.10; 26.10; 2.11; 9.11.2023	6
7	1B-b_c	5.10; 12.10; 19.10; 26.10; 2.11; 9.11; 16.11.2023	7
8	1B-b_{nfc}	5.10; 12.10; 19.10; 26.10; 2.11; 9.11; 16.11; 23.11.2023	8
9	2A-b_n	selections are similar to 1A-b_n and 1A-b_p	12
10	2A-b_p	selections are similar to 1A-b_n; 1A-b_p and 2A-b_n	12
11	2A-b_c	5.10; 12.10; 19.10; 26.10; 2.11; 9.11; 16.11; 23.11; 30.11; 7.12.2023	10
12	2A-b_{nfc}	5.10; 12.10; 19.10; 26.10; 2.11; 9.11; 16.11; 23.11; 30.11; 7.12.2023	10
13	2B-b_n	5.10; 12.10; 19.10; 26.10; 2.11; 9.11.2023	6
14	2B-b_p	5.10; 12.10; 19.10; 26.10; 2.11.2023	5
15	2B-b_c	5.10; 12.10; 19.10; 26.10; 2.11; 9.11; 16.11; 23.11.2023	8
16	2B-b_{nfc}	5.10; 12.10; 19.10; 26.10; 2.11; 9.11; 16.11; 23.11.2023	8
17	2A	5.10; 12.10; 19.10; 26.10; 2.11; 9.11; 16.11; 23.11; 30.11; 7.12.2023	10
18	2B	5.10; 12.10; 19.10; 26.10; 2.11.2023	5

Table 4

Results of statistical processing of the results on determining the impact of packaging on the terms of retting

Source of variation	*SS*	*df*	*MS*	*F*	*P*-value	*F* critical
Between groups	2166.855	3	722.285	6.904122743	0.000655642	2.816465817
Within groups	4603.125	44	104.6165	–	–	–

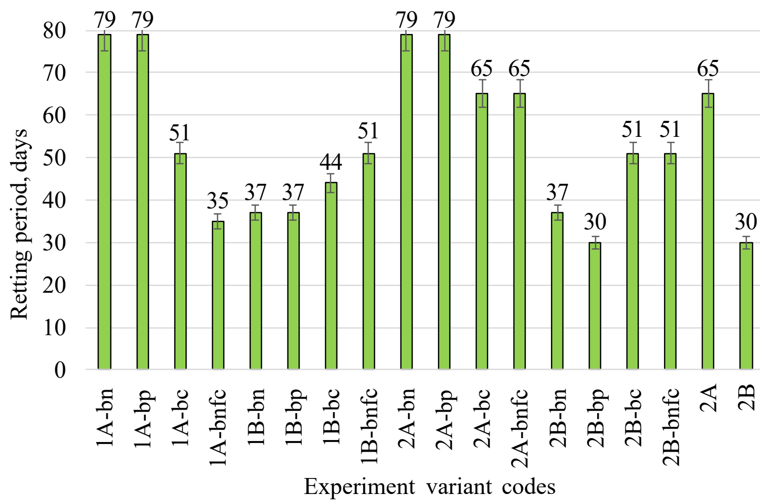


Fig. 2. Terms of retting

The presence in the first group (30 days of retting) of options with only horizontal placement of the stems indicates certain advantages of this technique for their arrangement. However, in the second group (37 days of curing), the same preparation terms were established in the 1B-b_n and 2B-b_n variants, which are similar in terms of preparation conditions (flattened stems, natural bag). However, the 1B-b_n variant involves a vertical position, and the 2B-b_n variant involves a horizontal position. The tendency of the terms to coincide (51 days) was recorded for the 1B-b_{nfc} variants (freshly cut stems, vertical position, flattened, natural bag) and the 2B-b_{nfc} variant (freshly cut stems, horizontal position, flattened, natural bag). The above-noted coincidence of preparation times is also observed in the group (65 days) for the same type of 1A-b_{nfc} and 2A-b_{nfc} variants with the difference only in the technique of placing the stems – horizontal or vertical.

The terms of preparation of retted stalks in bags of natural and polypropylene unflattened stems under conditions of their vertical installation exceeded the corresponding terms by 1.55 times in comparison with those of cellophane (Fig. 3, *a–c*).

Flattened stems, under the conditions of their vertical installation in natural and polypropylene bags, turned into retted stalks 1.19 times faster than in cellophane bags. With their horizontal placement, the indicated exceeded terms of retting amounted to 1.38 times (Fig. 3, *a–c*).

It was noted that the terms of retting of unflattened and flattened stems in natural and polypropylene bags coincided (Fig. 3, *a, b*). The results of retting using flattened stems in cellophane bags were characterized by a 16 % reduction in terms when placed vertically, compared to unflattened ones, and by 27.5 % when horizontally placed, respectively (Fig. 3, *c*).

The results of statistical treatment of the acquired data on changes in the terms of retting are given in Table 5.

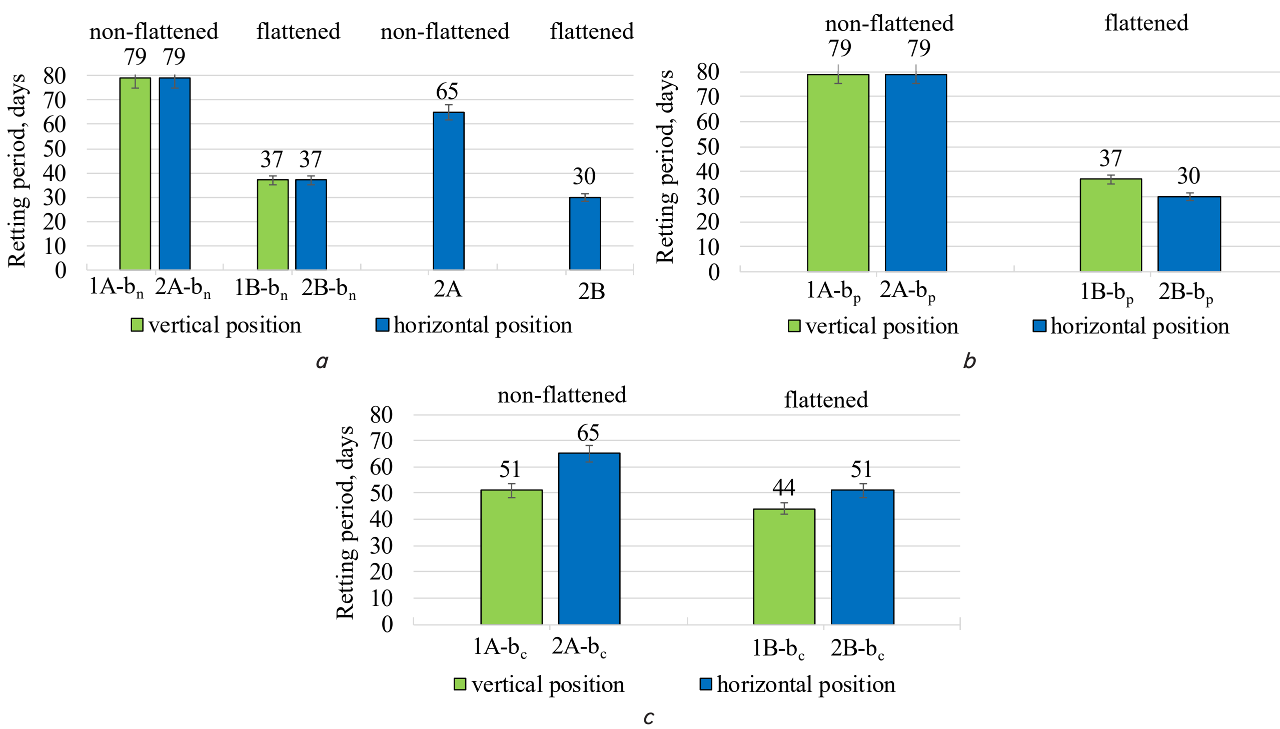


Fig. 3. Diagram of changes in the terms of retting: *a* – natural bag; *b* – polypropylene bag; *c* – cellophane bag

Table 5

Statistical treatment of the results of changes in the terms of retting

Source of variation	*SS*	*df*	*MS*	*F*	*P*-value	*F* critical
Between groups	3641.972	11	331.0883	2.778658931	0.002804192	1.861867708
Within groups	15728.33	132	119.154	–	–	–

As evidenced by the data given in Table 5, the results of changing the timing of retting are statistically significant. There are real differences between groups that are believed to be valid and not random. The studied factors exert an influence on the resulting variable.

5. 2. Results of determining the influence of stem flattening on the time of retting

The results of statistical treatment of the acquired data to determine the influence of flattening of stems on the timing of retting are given in Table 6.

It should be noted (Table 6) that the differences between the groups are sufficient. Under such conditions, they are considered reliable and statistically significant. There are real differences between the mean values of the groups, which makes it possible to classify them as non-random. This confirms the influence of the studied factors on the resulting variable.

In flattened stems (Fig. 4, *b*), the time of retting under the conditions of vertical and horizontal placement coincided in natural bags, as well as in the vertical position in polypropylene bags (37 days). As noted above, the preparation time for flattened stalks under the conditions of their horizontal placement in polypropylene bags was 30 days. The specified indicator is 1.23 times less than in natural and polypropylene bags, 1.47 times in cellophane bags with vertical stems, and 1.7 times less than in cellophane bags with their horizontal position.

The term of retting using flattened stems under the conditions of vertical position of natural and polypropylene bags was 37 days (Fig. 4, *a*). The duration of retting in cellophane bags was 44 days (19 % more), in natural bags with freshly cut stems – 51 days (38 % more than those with 37 days of preparation).

The results shown in Fig. 4, *a, b* demonstrate the coincidence of the terms of curing of unflattened stems in vertical and horizontal positions (79 days) under the conditions of retting in natural and polypropylene bags. The term of retting of non-flattened stems in cellophane bags in a vertical position was 51 (days), which is 1.55 times less than in natural bags and polypropylene bags. In a horizontal position, the preparation time of the above stalks was 65 days, which is 1.22 times less than in natural and polypropylene bags.

5. 3. Results of determining the influence of positioning the package of stems on the timing of retting

In cellophane bags, changing the position of stems from vertical to horizontal one led to an increase in the time of retting. For unflattened stems, the specified increase was from 51 to 65 days (1.27 times), for flattened stems from 44 to 51 days (1.16 times) (Fig. 5, *b*, 6).

The change in the position of retted stalks (Fig. 5, *a, b*) for different burlap materials, flattened and non-flattened stems was characterized by different indicators. With vertical position of natural, polypropylene, cellophane bags for flattened and non-flattened stems, the reduction in the time of retting was 2.14 times, 1.16 times, and for horizontally placed 2.14, 2.63, 1.27 times, respectively.

For freshly cut stems (Fig. 5, *a, b*) under conditions of vertical and horizontal position of the natural bag flattening of the stem reduced the time of retting by 1.27 times. The technique of placing the bag on the surface did not affect the regularity of the retting process.

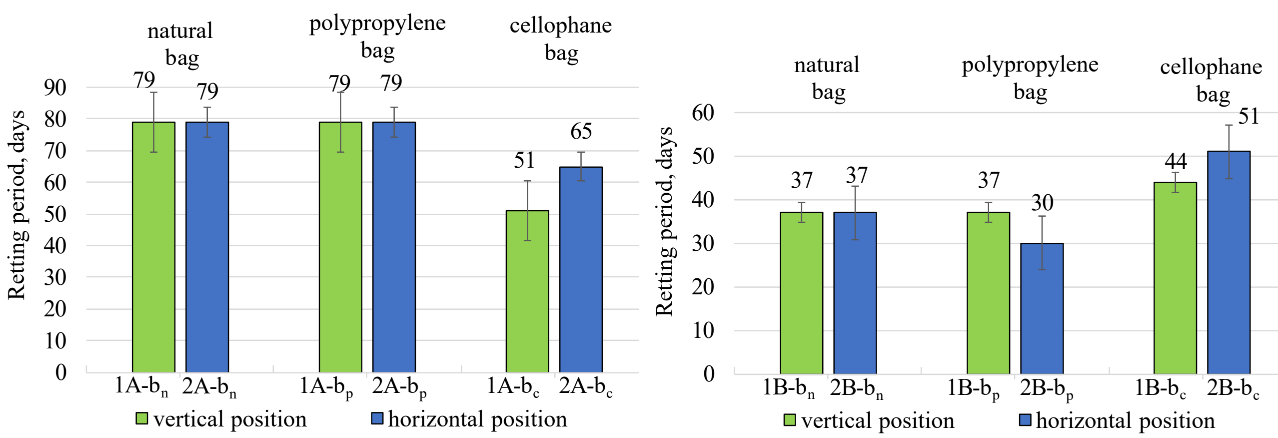
Comparing the results of experiments 2A and 2B, it was noted that their preparation times differ by 2.16 times (Fig. 7). The main reason for this difference, other conditions being equal (horizontal placement of stems, weekly watering twice a week), is the presence of flattening in variant 2B. That is, flattening the stems accelerated the time of retting by 2.16 times.

A two-fold increase in the amount of moisture for unflattened stems under the conditions of horizontal placement of natural bags reduced the time of retting by 1.22 times (Fig. 7). For flattened stems, the specified shortening of terms was 1.23 times (Fig. 8).

Table 6

Results of statistical treatment of the acquired data to determine the impact of flattening of stems on the timing of retting

Source of variation	*SS*	*df*	*MS*	*F*	*P*-value	*F* critical
Between groups	826.2642	3	275.4213889	3.659670412	0.019348685	2.816465817
Within groups	3311.375	44	75.25852273	–	–	–



a *b*

Fig. 4. Diagram of changes in the time of retting depending on the type of mechanical action: *a* – unflattened; *b* – flattened

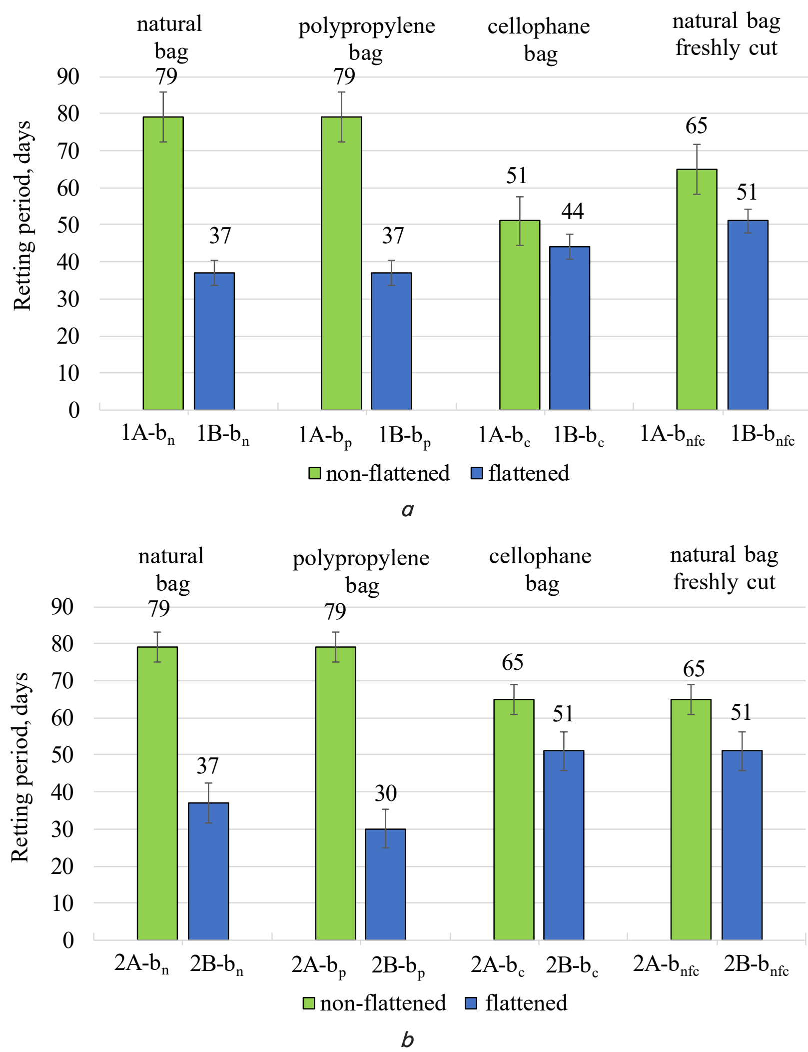


Fig. 5. Diagram of changes in the time of retting, depending on the option of placing the stems on the soil surface: *a* – vertical position; *b* – horizontal position

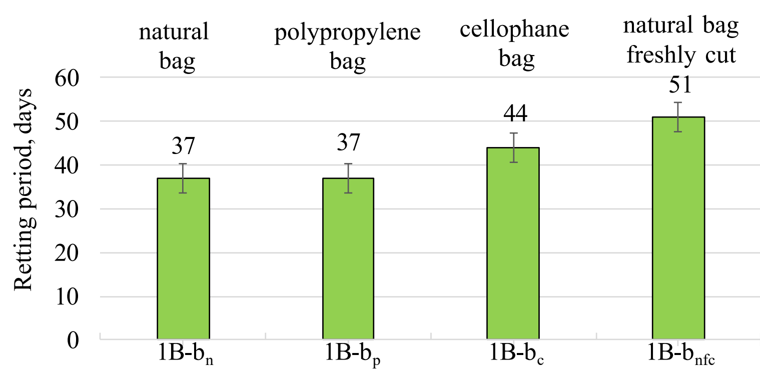


Fig. 6. Diagram of changes in the time of retting under the conditions of vertical position of flattened stems

It should be noted that there is a certain difference in the results of the preparation of retted stalks from stalks previously dried in bundles with the seed part, threshed and directed to retting. This difference is evidenced by the results in Fig. 6, *a*, 7. If the flattening of previously cured stems leads to a reduction in the time of retting by 2.14 times under the conditions of vertical and horizontal placement (Fig. 7), then for freshly cut stems this reduction is determined by an indicator of 1.27 times.

The process of flattening the stems significantly affected the results of the research. The destruction of the flattened dry stem led to the separation of the core, which enabled more intensive microbiological processes of its transformation into retted stalks than in freshly cut stems.

Under these conditions, the retting time of flattened freshly cut stems is 1.39 times longer compared to pre-prepared ones, both when they are positioned vertically and horizontally.

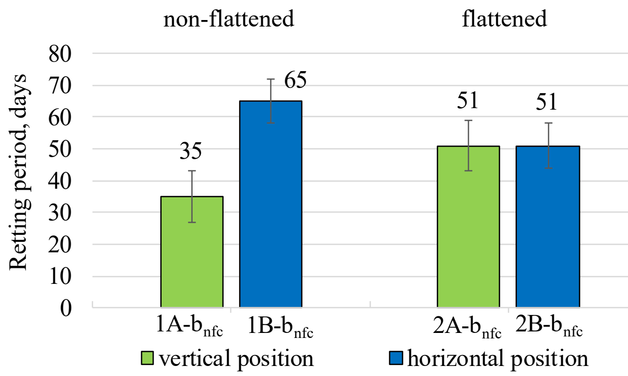
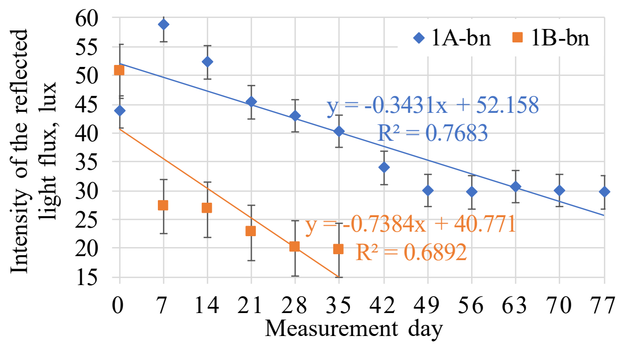


Fig. 7. Diagram of changes in the timing of retting (natural bag, moistening twice a week)

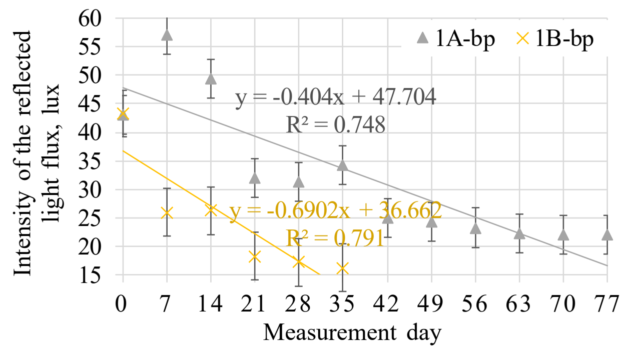
Unflattened and flattened freshly cut stems (Fig. 7) in natural bags with their vertical and horizontal positioning were characterized by the same values of the indicator of shortening the time of retting – 1.27 times.

5. 4. Results of investigating the quantitative and qualitative indicators of produced fiber

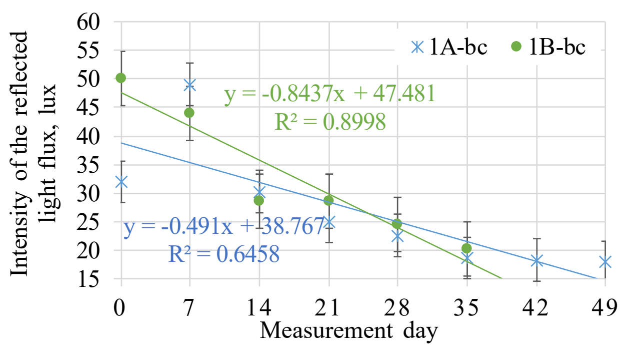
It was noted that the intensity of the reflected light flux from the stem, which was determined by the device, in the case of reaching the retting phase, changed from the initial 32.0 lux for unflattened (variant 1A-b$_c$), with vertical position, to 18.0 lux (Fig. 8, *a–c*). Under conditions of vertical position of flattened stems, the intensity upon reaching the retting phase varied from the initial 50.7 (1B-b$_n$), 43.3 (1B-b$_p$), 50.0 (1B-b$_c$), 28.7 (1B-b$_{nfc}$) to the value of 19.7 lux, 16.3, 21.3, 16.3 lux, respectively. Under the conditions of horizontal placement of flattened stems (options 13–16), the intensity values under the conditions of reaching the retting phase were as follows: 2B-b$_n$ – 20.3 lux, 2B-b$_p$ – 19.0 lux, 2B-b$_c$ – 23.7 lux, 2B-b$_{nfc}$ – 17.3 lux (Fig. 9, *a, b*).



a

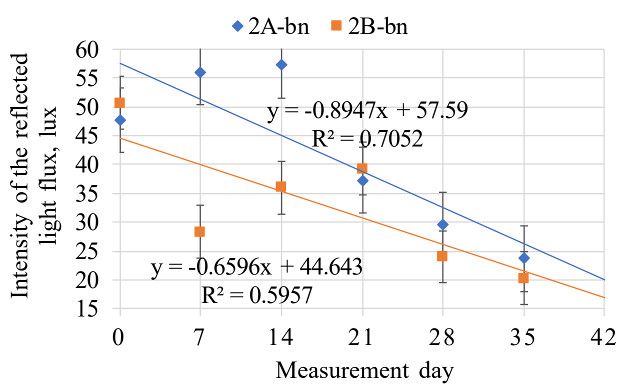


b

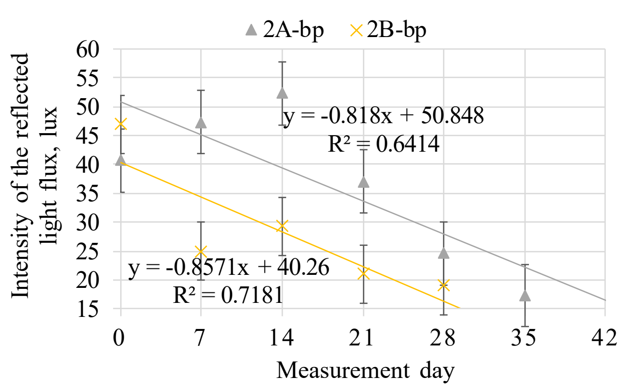


c

Fig. 8. Changes in the intensity of the reflected light flux according to the device under the conditions of vertical position of stems: *a* – natural bag; *b* – polypropylene bag; *c* – cellophane bag



a



b

Fig. 9. Changes in the intensity of the reflected light flux for stems under conditions of horizontal arrangement of stems: *a* – natural bag; *b* – polypropylene bag

A certain decrease in the breaking load of the fiber (Fig. 10, 11) was noted during the curing of retted stalks in variants with flattened stems (3.5–8, 13–16, 18) and non-flattened stems (9, 11, 12, 17). However, no clear dependence of the reduction of the breaking load was noted in all variants (1, 2, 4, 10). The lowest value of the specified indicator was found in the variants of curing hemp retted stalks from freshly cut stems flattened in a vertical position (8–12.0 daN, horizontal 16–5.0 daN) and not flattened (vertical 4–7 daN; horizontal 12–3.5 daN).

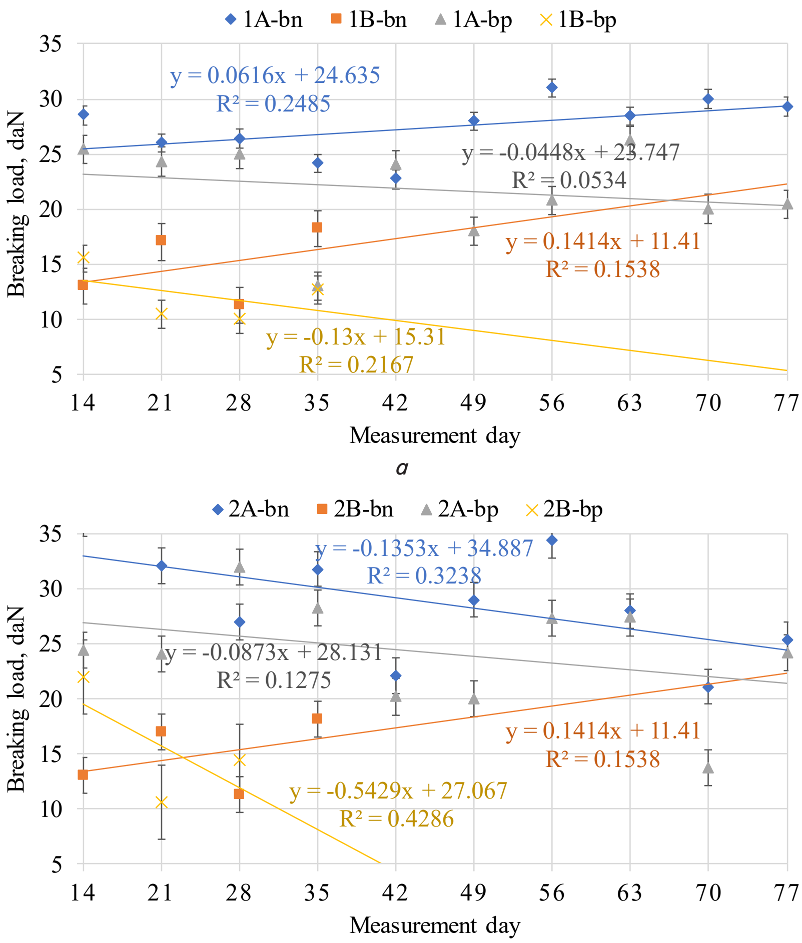


Fig. 10. Changes in the breaking load of the fiber depending on the location of the package: *a* — vertical position; *b* — horizontal position

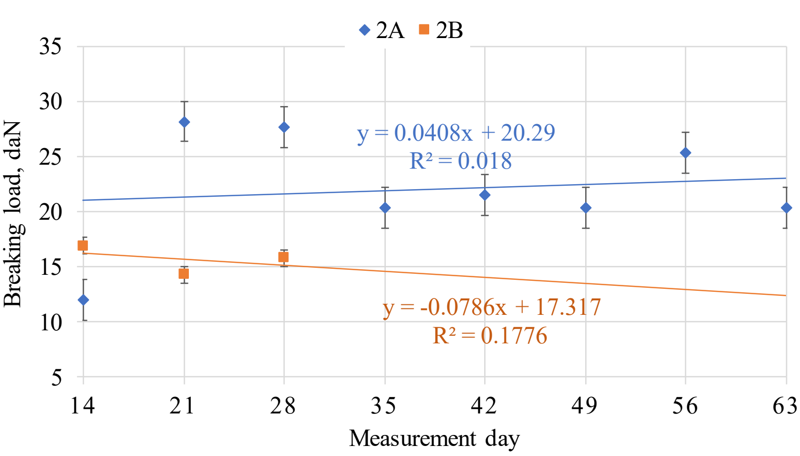


Fig. 11. Change in breaking load under the conditions of curing the stems in a horizontal position in natural bags (moistening twice a week)

The indicated lowest value was also determined in the flattened variants of cured retted stalks in cellophane bags in a horizontal position (15–7.7 daN). According to the indicator of fiber yield, certain patterns of decrease have been established only in some variants (5–8, 12–18).

Table 7 gives indicators of the linear density of fiber at the end points of curing the hemp retted stalks for some variants of their preparation. The linear density of the fiber (Table 7) varies depending on the applied methods for processing the stems. For the 1A-b_c variant, the linear density is 50.5 tex, which is one of the lower indicators compared to other variants (1B-b_c – 87.1 tex, 2B-b_p – 83.3 tex). This indicates that the choice of retting technique affects the quality and characteristics of the fiber.

Table 7

Indicators of the linear fiber density at the end points of curing the hemp retted stalks for some variants of their preparation

Variants	Linear density, tex
1A-b_c	50.5
1B-b_p	87.1
2A-b_c	65.1
2B-b_p	83.3

In the 1B-b_c and 2B-b_p options, a higher level of linear fiber density was established. Stalk flattening in combination with processing in cellophane or polypropylene bags helps obtain fiber with higher density indicators.

6. Discussion of results of investigating the factors that intensify the terms of retting

Packing of hemp stalks and the application of mechanical actions to them significantly change the terms of retting and the quality indicators of the produced fiber. The cellophane package prevents the natural circulation of air, which slows down the processes of microbiological decomposition of pectin substances. As a result (Fig. 3, 4), an increase in the time of retting was established compared to natural or polypropylene packaging. Similar results were obtained under the conditions of evaluating the impact of packaging materials on heat and mass exchange [20]. It was noted that the use of packaging material, which limits the natural circulation of air, leads to a change in the processing time of products.

Mechanical actions on the stems significantly shorten the time of retting (Fig. 5). In particular, flattening destroys the outer shell of the stems, which makes it easier for microorganisms to penetrate and accelerates the curing process. The terms of retting are shortened to 30–37 days, while these terms are much longer in unflattened stalks. The above results are consistent with [21], which noted a reduction in the preparation time of flax retted stalks by 3–9 days under the conditions of flattening the stem part of stems.

The presence of sufficient moisture contributes to the activation of microbiological processes necessary for the decomposition of stem tissues and helps speed up the retting process (Fig. 7). In the variants where the stems were moistened twice a week, the time of retting was reduced compared to those that were moistened only once a week. Our results are consistent with [22], which established the influence of the humidity level on the development of fungal pathogens (*Fusarium oxysporum*).

The horizontal arrangement of stems (Fig. 6) contributes to a more uniform influence of natural factors, such as humidity and temperature, which ensures shorter retting times compared to a vertical position. These factors indicate that the timing of retting largely depends on the combination of technological solutions.

A feature of our research is a comprehensive approach to the intensification of the retting process, which takes into account the influence of various factors. This has made it possible to shorten the time of retting and achieve better fiber quality indicators compared to traditional methods.

There are studies on certain factors affecting the process of retting [12]. The main differences of our studies include a comprehensive assessment of a number of factors intensifying the process of hemp retting.

Our research has confirmed the effect of mechanical destruction of the stem shell on the penetration of microorganisms. Due to this, biological processes are accelerated. In [23], the emphasis is on achieving the maximum amount of fiber. However, quality issues need to be refined. The proposed methodical approaches make it possible not only to reduce the time of retting but also ensure higher fiber quality. The sources of the noted are the use of mechanical action on the stem in combination with other factors.

It should be noted that the proposed methodical approaches to retting, as well as the achieved research results, have been established within certain agrotechnical and climatic conditions. Accordingly, the evaluation of the effect of ripeness and varietal characteristics of hemp on the time of retting requires special research.

It is well known that the effectiveness of methods depends on the type of stems (freshly cut or dry). It seems natural to adapt the method in accordance with the characteristics of the raw material. The presence of sufficient humidity significantly shortens the time of retting. The results of this study are most effective in a controlled environment where regular humidification is possible. For production conditions without control of external factors, such as natural curing in open areas, the application of the received recommendations may be limited. Mechanical flattening of stems, which was carried out under laboratory conditions, may have limited reproducibility on an industrial scale. In the laboratory, flattening was performed with constant parameters of pressure and the gap between the rolls, which ensured uniform destruction of the stems. However, in industrial settings, equipment often has wider parameter tolerances, and pressure control and flattening stability can vary by equipment type and operating mode. This can lead to uneven flattening, making it difficult to reproduce the intensification effect. With a lack of moisture or excessive dryness, external factors can significantly affect the biological processes of curing the retted stalks. Depending on the climatic conditions of a specific region, it is advisable to adjust the frequency of moistening and the type of packaging material to obtain the desired quality indicators. The best results were achieved with horizontal placement of flattened stems with regular moistening in natural or polypropylene bags. Deviation from these conditions may increase the curing time or reduce the quality indicators of the final product. Despite this, the results remain useful for further improvement of the processes of retting under industrial conditions, especially if adapted to specific production conditions.

Lack of economic analysis, insufficient consideration of climatic factors, limited range of tested packaging materials, and lack of testing under industrial conditions are among the shortcomings of the research. In the future, the indicated shortcomings can be eliminated through specialized additional studies, which should include the noted directions.

Since the weather and climate conditions significantly affect the biological processes that are responsible for the curing of retted stalks, the study of adaptation mechanisms under different climatic conditions is a promising area. To conduct such research, it is advisable to create several experimental plots. Diversification of the types of mechanical impact on different parts of the stem, ensuring their uniformity should also be considered a priority area of research.

It is advisable to continue experimental research with the aim of accumulating informational data, expanding and clarifying the patterns defined, which determine promising directions for the intensification of biological processes under the conditions of hemp stalk retting.

7. Conclusions

1. It has been established that flattening precured stems under the conditions of their vertical and horizontal placement shortens the time of retting by 2.14 times, and that of freshly cut stems – by 1.27 times.

2. It has been noted that placing the flattened stems in natural and polypropylene bags, in comparison with cellophane bags, accelerates the time of retting by 1.19 times in a vertical position, and by 1.38 times in a horizontal position.

3. It was established that the time of retting for horizontally placed flattened stems with weekly moistening twice a week is 2.16 times shorter than for non-flattened ones.

4. The lowest fiber breaking load value of 5.0 daN was established for the retted stalks obtained from freshly cut flattened stems in a vertical position, as well as in unflattened stems in vertical (7.0 daN) and horizontal (3.5 daN) positions.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

This paper was supported by the HEI-TREATY (Nurturing deep tech talents for clean and sustainable energy conversion) project under the EIT HEI Initiative "Innovation Capacity Building for Higher Education" funded by the European Union.

Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

The authors express their gratitude to the Institute of Bast Crops at the National Academy of Agrarian Sciences of Ukraine for support and assistance in conducting experimental research.

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