TECHNICAL AND TECHNOLOGICAL SOLUTIONS FOR PREPARING FLAX RAW MATERIALS FOR PROCESSING
/
ТЕХНІКО-ТЕХНОЛОГІЧНІ РІШЕННЯ ПІДГОТОВКИ ЛЛЯНОЇ СИРОВИНИ ДО ПЕРЕРОБКИ

Berezovsky Yu.[1)], Kuzmina T.[1)], Yedynovych M.[1)], Boyko G.[1)], Lyalina N.[2)], Holovenko T.[3)]
[1)] Kherson National Technical University, Kherson / Ukraine;
[2)] Kyiv National University of Construction and Architecture, Kyiv / Ukraine;
[3)]Lutsk National Technical University, Lutsk / Ukraine
Tel: +38 (099) 023-62-32; E-mail: berezov.sky.ua@gmail.com
DOI: https://doi.org/10.35633/inmateh-64-22

***Keywords:** flax; retted straw; storage methods; humidity; preservation.*

ABSTRACT
The article contains theoretical and experimental researches in the field of the preservation of flax raw material of high moisture content. In the article, factors that are worsening the quality of flax raw material, resulting in non-observance of agrotechnical and technological requirements of preparing, collecting, harvesting the stem material, adverse weather conditions and other factors, are considered. The objective of this paper is to study the influence of preservation agents' concentrations and of hollow structure device on the quality of flax raw material during long-time storage. In the article, the influence of aqueous preservatives' concentration, humidity, storage length on the quality of fibrous products, obtained as a result of processing stem material, is analyzed. The influence of the device of hollow structures, as an alternative to preservatives, on the storage process of bast crops stem material was evaluated. The method of flax retted straw storage is described, actions of the main factors influence on the strength of fibers are analyzed. It is demonstrated, that prolongation of flax raw material preservation time can be made by using preservatives without considerable wastes of quality.

РЕЗЮМЕ
Стаття містить теоретичні та експериментальні дослідження в галузі збереження лляної сировини підвищеної вологості. У статті розглянуто фактори погіршення якості лляної сировини, що пов'язані з недотримання агротехнічних та технологічних вимог підготовки, збирання, заготівлі стеблового матеріалу, несприятливими погодними умовами та іншими факторами. Завданням роботи є вивчення впливу консервантів та установки порожнистих структур на якість лляної сировини при тривалому зберіганні. У статті проаналізовано вплив концентрації водних розчинів консервантів, вологості, терміну зберігання на якість волокнистої продукції, отриманої у результаті переробки стеблового матеріалу. Здійснено оцінку впливу установки порожнистих структур, як альтернативи консервантам при зберіганні стеблового матеріалу луб'яних культур. Описано методику проходження зберігання лляної трести, проаналізовано дії основних факторів впливу на міцність волокна. Доведено, що використання консервантів дає можливість подовжити термін зберігання лляної сировини без значних втрат її якості.

INTRODUCTION
The production of industrial crops occupies an important place in the modern world economy. Crops that require further industrial processing are considered technical. These include fiber, sugar, oil, tannin, and rubber-bearing crops. Fiber crops are one of the most important industrial crops *(Holovenko T.N. at. al., 2018; Roland J. at. al., 1996)*. They comprise cotton, flax, hemp, abacus, jute, and sisal. The world leaders in flax production are France, Russia, Poland, Germany, Belgium, leading producers of hemp are Canada, China, abacus - the Philippines, jute - India, Bangladesh, and sisal - Tanzania, Kenya, and Brazil.

One of the traditional industrial crops having long been cultivated in Ukraine is flax. "Flax fiber is suitable for the production of non-woven materials, technical textiles and paper" (*Dudarev I. at. al., 2020*). "Studies have shown the prospects of using small-sized fuel rolls from oleaginous flax waste as a new type of solid biofuel" (*Yaheliuk S. at. al., 2020*)". It is a valuable raw material for textile, construction, pulp and paper, pharmaceutical and other industries.

Under the development of industrial production of synthetic fibers, expanding their range, the value of economic and hygienic properties of flax fiber remains unchanged *(Abbar B. at. al., 2017; Berezovsky Yu.V., 2018).*

The general technology at the enterprises of primary processing provides drying of raw materials with high moisture content on drying installations to normalized values and its further storage in a fluffed state separately from the main amount of raw materials and its immediate processing *(Dudarev I. at. al., 2020)*.

The loss of raw materials during storage is mainly due to excessive moisture content, which is a consequence of the improper preparation and stacking of raw materials, raw materials harvesting in autumn and spring when humidity is extremely high. With the high moisture content of the raw material, the temperature inside the stacks rises, which is accompanied by self-heating of the material and makes it unusable. Therefore, in the process of long-term storage, it is important to ensure the preservation of the quality of flax raw materials due to the negative activity of a large number of cellulose-destroying fungi and bacteria, which significantly reduce the technological value of fiber *(Didukh V.F. at. al., 2008)*.

Microbiological processes that cause complete damage to flax fiber during storage have been studied by various scientists *(Khilevich V.S., 1992; Kyryliuk R.M., 1994; Ostrik N.M., 1983)*. Microbes have been shown to cause hydrolytic dissolution of proteins and other nitrogenous organic substances by proteases. The decomposition of the constituent substances is possible only when the destructive microorganisms have all the necessary conditions for their development: the optimum temperature, moisture content, the appropriate reaction of the environment, the necessary nutrients, and other factors. Low temperatures slow down biochemical processes, so at "a temperature of 5°C, the biological processes completely stop and the straw is kept in the state of natural preservation *(Kuzmina T.O. at. al., 2018)*". Freshly harvested straw is more resistant to pectin-destroying fungi than dried flax stems, and the preservation of quality indicators of flax raw materials can be carried out at a moisture content of no more than 25%, and in a roll - no more than 23%; this rule often forces to leave raw materials on flax harvesting sites, which can lead to the loss of fiber strength.

Theory and practice of harvesting and storage of flax and hemp raw materials, the application of new forms of packaging and technological equipment, the use of high-performance equipment for the preparation and processing of bast raw materials, which are presented in *(Gopu R. Nair at. al.; 2013; Mankowski J. at. al., 2018; Mukhin V.V., 1985; Kuzmina T.O. at. al., 2018)*, give grounds to assert that at the present stage of light industry development in Ukraine obtaining significant results in the flax and hemp processing is possible only by addressing the issue of ensuring the initial quality characteristics of raw materials, compliance with the necessary technological parameters, guaranteeing the preservation of physical and mechanical properties, implementing innovative solutions to the problems of preparation, storage, and processing in the industry taking into account anatomic and physical and mechanical properties of bast crops. "Under certain investment attraction conditions and introducing innovative technologies the industry will acquire considerable potential, which will help to increase the domestic raw materials competitiveness, leading to flax and hemp production revival (*Berezovsky Yu.V. at. al., 2020)"*.

World experience in the preservation of products, characterizing the effect of negative microflora suppression, distinguishes mainly the chemical method of exposure using chemicals; temperature method providing the regulation of storage temperature; method of storage in gaseous media in a controlled atmosphere - with the selection of gas and temperature parameters. "Chemical or biological preservation can provide much less dependence of storage technology on changing weather conditions *(Kuzmina T.O. at. al., 2018)*". Each method in its own way characterizes the impact on the destructive microflora, their nature and degree of influence depend on the nature and concentration of substances, processing conditions, integrity, and controllability of storage facilities, as well as the quantitative and qualitative composition of microflora, which determines the relevant economic indicators, efficiency and use of special complex equipment.

As the artificial drying of flax raw materials is not currently widely used in practice due to significant heat costs and metal consumption of equipment, the domestic processing industry needs to find and develop a new rational economic technology for storing flax retted straw of high-moisture content.

Based on the theoretical and experimental studies performed, the inefficiency of using traditional technology of preparation, storage, and processing of domestic bast crops has been established, which is due to the significant dependence of fiber on the initial state of raw material, especially moisture content, development of cellulose-destroying processes in the stem material. Analysis of technical and technological perspectives revealed in *Berezovsky Yu.V. (2018)*, indicates that to obtain high-quality fiber at the end of the production process chain, highly dimensional equipment is used that requires significant energy costs, which, to date, is simply impractical and virtually causes economic inefficiency of this approach. Therefore, "introduction of resource-saving technology will increase the profitability of linseed cultivation" *(Dudarev I. at. al., 2020)*.

Currently, some discussions are taking place and the relevant scientific basis of modern technologies are being developed for harvesting, preparation, storage, processing of bast raw materials, use of high-tech modern equipment for bast material preparation, application and implementation of special measures and effective ways to preserve qualitative and quantitative characteristics of flax straw and retted straw *(Bobyr S. at. al., 2014; Dudarev I. at. al., 2020)*. However, to date, such issues have not been sufficiently resolved from the standpoint of rational use, feasibility, and versatility of application for different types of bast raw materials.

It has been found that many scientists are involved in the preparation, harvesting, and storage of bast crops, but no reliable methods or techniques have yet been established. Nowadays, in foreign and domestic practice for prolonged storage, a range of promising chemical compounds is used that has antioxidant, fungicidal, and bactericidal properties that inhibit the activity of the microflora, as well as desiccants *(Bobyr S. at. al., 2014; Kuzmina T.O. at. al., 2018)*, which dehydrate and dry the stem material, absorb or chemically bind water within, but many storage issues still remain unresolved. Therefore, there is a need to continue the search for new technologies that would ensure the preservation of the physical and mechanical properties of flax raw materials and would be affordable and cost-effective.

Solving the issue of finding available preservatives, that can affect the viability of microorganisms and ensure the preservation of the quality of flax raw materials in the long run, is necessary for the domestic processing branch of the light industry. Development and introduction of accessible and effective technology of preservation of flax retted straw in production allow optimizing the process of storage of flax raw materials of high moisture content, to establish rational storage terms of bast fiber without considerable quantitative and qualitative losses during preparation and primary processing.

MATERIALS AND METHODS

Today, the textile industry remains the main consumer of flax stems. Given that the world market for silk is becoming more expensive every year, the prospects for textile producers are growing. At the same time, Ukrainian scientists predict that after setting up processing facilities, Ukraine may sow flax up to 25-30 thousand hectares in the next 5-10 years. The European Union has refused to import Canadian modified oilseed flax. Therefore, there is a deficit in Europe, which can be offset by purchasing flax from Ukraine and other neighboring countries *(Berezovsky Yu.V. 2018)*. World flax production and flax seed exports in 2019-2020 reached 3.11 million tons. According to OilWorld experts, world flax seed production in the 2020-21 marketing year could increase to 3.29 million tons *(Agronews.Ua, 2021).* Ukrainian producers can only benefit from this deficit - they now have every chance to take a worthy place in the world flax market, but the dynamics of changes in flax sown areas in Ukraine for 2000-2019 is still far from being optimistic (Fig. 1).

Fig. 1 - Dynamics of flax sown areas in Ukraine for the period 2000-2019
(constructed according to the Ukrainian State Statistics Service)

In order to achieve far-reaching opportunities, domestic production needs to solve the problems associated with harvesting, preparation, and storage of bast raw materials, as it is at these stages that a significant amount of it is lost. It is known that the decrease in the quality of flax retted straw is associated with untimely spreading or removing it from rettery, during which due to adverse weather conditions, destructive microflora causes significant damage to flax production. During the process of aging and storage of wet flax material, there is a change in its chemical composition and physical and mechanical properties, its strength is lost, the separability increases *(Khilevich V.S., 1992; Kuzmina T.O. at. al., 2018)*.

It is important not only to process the entire yield of flax straw into a quality retted straw but also to preserve the quality of the retted straw already obtained by spreading in the process of long-term storage in flax plants after mass harvesting. Due to the high infestation of fungi and bacteria, and the increased moisture content, the retted straw rapidly loses quality indicators and the technological value of the fiber decreases *(Bobyr S. at. al., 2014; Kuzmina T.O. at. al., 2018).*

There are several ways to store flax raw materials with high moisture content. The storage of bast material is achieved by bringing it to the normatively accepted condition in terms of moisture content during drying or by treatment with chemical and biological substances. Conventional natural drying processes are complicated by the high density of the material in the packaging rolls, so artificial drying is a reliable technology for storing bast material. Although due to the significant energy consumption as a method of maintaining the quality of raw materials, it has been more widely used abroad than in Ukraine. In world practice, fungicides and antiseptics are used for chemical plant protection. Fungicides are used against fungi, bacterial and viral diseases, often for seed treatment. Antiseptics are substances that affect microorganisms. They are used in various sectors of the economy as additives to the material that permeates it. Thus, the action of ammonia, ammonia salts during storage is manifested as the action of fungicide, bactericide, rodenticide and fibrilizer, and chemicals show technical and economic efficiency.

The research of American scientists in the direction of product storage is of interest. They followed an unconventional way of extending the storage term of agricultural products, using a chitin substance contained in the shell of arthropods *(Semakov V.V., 1994)*. This substance in the form of a chitin derivative dissolved in water is sprayed as an aerosol, forming a semipermeable shell on the surface of the products. Researchers at the University of Washington justify the principle of chitosan action slowing down of the process of respiration of products during storage, which protects them from fungal infections.

American scientists describe two more non-traditional methods of plant protection, the effect having been tested in laboratory and field conditions. One of them is the use of so-called coniferous wax as a protective layer, which is a by-product of chemical processing of pine and spruce needles *(Semakov V.V, 1994)*. Sprayed similarly to chitosan, the wax forms a thin film on the product surface, inhibiting the passage of oxygen and metabolic products, and the use of water-gasoline emulsion of chlorophyll-carotene paste, which is obtained from pine and spruce needles, resulting in prolonged storage.

Practice shows that in order to obtain high-quality end products of flax processing during storage of flax raw material with high moisture content, it is necessary to constantly monitor its condition, which is often influenced by natural factors and the microflora that surrounds and develops under appropriate conditions. One way to reduce such losses may be to increase the use of balers by harvesting flax straw and high moisture content retted straw using preservatives that reduce the technology's dependence on weather conditions. Applying liquid preservatives in the roll forming process enables more uniform distribution of preservatives within the raw material *(Boyarchenkova M.M. at. al., 1988; Khilevich V.S., 1992)*.

In domestic practice, biologically active substances "Trichodermin" and "Fitosporin-M" *(Bobyr S. at. al., 2014; Kuzmina T.O. at. al., 2018)*, which have a fungicidal and bactericidal effect against cellulosolytic fungi and bacteria, have been successfully used for the storage of oil flax stems. In spite of the practical significance of these results, such studies are inherent in the stem material of oilseed flax in the southern regions of the country, which differs significantly in the properties and conditions of common flax straw and retted straw, which is the main source of flax fiber.

The use of technology for preserving high-moisture retted straw can reduce the cost of manual labor for harvesting raw materials in adverse weather conditions, significantly reduce energy consumption for artificial drying, and loss of fiber flax products.

All known preservatives used for storage of high-moisture retted straw do not have a set of necessary properties: efficiency, environmental safety and cheapness. That is why the development of effective ways to preserve the quality of flax raw materials is still quite relevant in modern conditions.

The studies on determining the effectiveness of preservatives, means, and methods of flax storage were guided by feasibility, ease of use, efficiency, and safety. Instrumental standard methods were used to verify the qualitative characteristics of flax raw material samples. During the experiments, the principle of a single difference was followed. At some research sites, treatment with preservative solutions, roll formation, and further studies were performed within one day, using the same instruments and equipment.

During the research, common flax varieties "Eskalina", "Charivny" were used, which were grown in farms and research areas of Zhytomyr region, and the soil growing conditions were typical for the flax zone. Flax cultivation for experiments was carried out in compliance with all technological conditions.

Typical flax stems, similar in morphological features to the predominant number of raw materials, were selected for the research. Initial research was performed on industrial packaging (rolls) of flax raw materials, and subsequent studies were carried out on small batches weighing 50 g with a density of 125 kg/m^3, allowing observing changes in flax stems, to determine the main regularity and causes of these changes, as well as the effectiveness of certain techniques. The mode of the storage process was applied at a temperature range of 15-20°C and relative moisture content of about 60-65%.

Aqueous solutions of carbamide, ammonium nitrate, aethonium, sodium carbonate, sodium chloride, and methanol were used as preservatives. The optimal distribution of preservative on flax stems is ensured by a specially designed cylindrical wing-shaped ejector (Fig. 2), and an irrigation system, which is installed above the place of formation of the flax retted straw roll *(Chursina, L.A., 2002).* The process of storage of high-moisture flax retted straw with the use of installation of hollow structures imitating beehives was also investigated. The section of the installation of hollow structures is shown in Fig. 3.

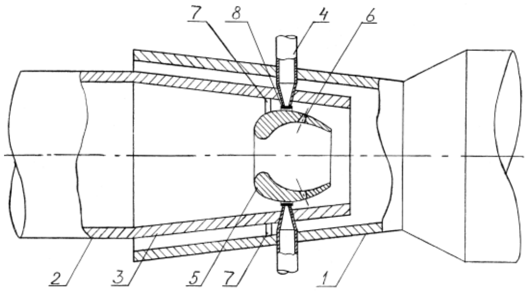

Fig. 2 - Ejector

1 - housing; 2 - active medium intake; 3 - duct reducer unit; 4 - passive medium intake; 5 - streamlined body; 6 - slit; 7 - rod; 8 - slot-shaped nozzle

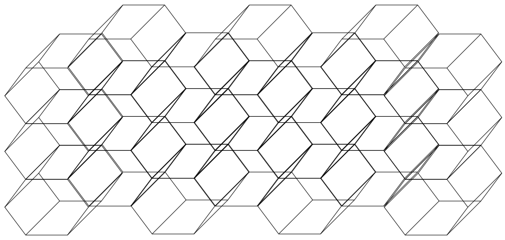

Fig. 3 – Cross-section of the installation part of hollow structures

The main components of the installation are hexagonal tubes, which can be made of different materials, with an inner diameter of 0.012 m. The hexagonal tubes are tightly connected and installed in a vertical position, which allows reproducing beehives. In this structure, an air flow is directed to the retted straw mass, which provides an aerobic storage environment.

To determine the effectiveness of the use of chemicals that were selected for research on the preservation of flax retted straw, the search for the optimal concentration of the above substances was carried out. According to the results of the scientific research scientists *(Boyarchenkova M.M. at. al., 1988; Khilevich V.S., 1992; Kyryliuk R.M., 1994)*, it was determined that the most expedient and cost-effective is the concentration of aqueous solutions of preservatives, not exceeding 10%. Therefore, the effectiveness of aqueous solutions of carbamide, ammonium nitrate, worked-out aethonium, sodium carbonate, sodium chloride, and methanol was investigated at the above concentration at retted straw moisture content of 30% and the duration of storage of high-moisture retted straw of 30 days (Table 1).

Table 1

Change in physical and mechanical parameters of retted straw under the influence of preservatives

Preservative type	Physical and mechanical parameters of retted straw		
	separability, conventional units	flexibility, mm	breaking load, daN
Carbamide	6.7	44	16.8
Ammonium nitrate	6.9	47	14.7
Aethonium	7.6	68	8.6
Sodium carbonate	8.1	53	5.7
Sodium chloride	8.3	64	2.6
Methanol	7.7	45	13.0
Initial indicators of retted straw	6.0	36.6	16.0
Control (without preservative)	8.8	74	3.1

RESULTS

The results of studies showed the ineffectiveness of the use of such preservatives as sodium carbonate and sodium chloride. They did not provide storage of high moisture content retted straw even for 30 days. But the preservative efficiency of aqueous solutions of carbamide, ammonium nitrate, worked-out aethonium, methanol was revealed. Although the aqueous solution of methanol showed a good preservative effect, it was excluded from the study due to environmental safety considerations. To conduct further research to identify optimal storage conditions for flax retted straw, the preservatives represented by aqueous solutions of carbamide, ammonium nitrate, worked-out aethonium were selected as the most effective, environmentally friendly, and feasible.

Based on a preliminary analysis of theoretical and practical research data and the application of mathematical experiment design, the following levels of variation of the above factors were determined: concentration of substances C, % (7.6; 8.8; 10); storage term T, days (30; 45; 60); moisture content in retted straw W, % (25; 30; 35). During the study, it was found that the lowest concentration of preservatives at which the preservative effect is observed is 7.6 %.

The results of research indicate that the flax raw material obtained from flax stems during storage using preservatives has higher physical and mechanical properties compared to flax raw material not having been treated. It was found that all the quality characteristics change during storage depending on the type of preservative. The values of physical and mechanical parameters indicate the possibility of storing retted straw of high moisture content. Thus, when using an aqueous solution of carbamide, positive results were obtained in options at the following levels of factor variation: 1) C = 7.6%; T = 45 days; W = 35%; 2) C = 7.6%; T = 60 days; W = 35%. Aqueous solution of ammonium nitrate also proved to be an effective preservative, when used, the physical and mechanical properties of flaxseed are at the appropriate level, except when the levels of factor variation are as follows: 1) C = 7.6%; T = 30 days; W = 25%; 2) C = 7.6%; T = 45 days; W = 30%; 3) C = 7.6%; T = 45 days; W = 35%; 4) C = 7.6%; T = 45 days; W = 30%; 5) C = 7.6%; T = 45 days; W = 35%.

Studies to identify the effect of aethonium on the storage process of flax retted straw were conducted at the same levels of variation as in previous research options. Based on the results obtained, it can be argued that worked-out aethonium proved to be a short-acting preservative. Aethonium significantly affects the process of storage for only 30 days. In comparison with the control, this preservative retains the physical and mechanical properties of flax retted straw only for a short period of storage. To increase the efficiency of the preservative force during a longer storage period, it is necessary to use aethonium of a higher concentration, but this leads to an increase in the cost of preserving high-moisture flax raw material.

As a result of the research analysis, it was revealed that in some cases at the specified concentration of the preservative solution and the established term of storage with an increase in flax retted straw moisture content its strength increases, although without application of preservatives the opposite process occurs. This trend can be explained by the fact that a sufficiently high solution concentration and long-term storage with increasing moisture content of flax raw materials facilitates the penetration of preservatives through the tissues of the stem to the inner cavity. At the same time, preservation occurs both in the middle of flax retted straw stems and outside them. At low retted straw moisture content, only external preservation of tissue occurs. Rotting and mold fungi can grow freely without hindrance, i.e. the conservation is not properly performed.

When comparing the effectiveness of the three preservatives, it should be noted that carbamide has the best and longer-lasting effect on the storage process of flax retted straw of high moisture content.

Installation of hollow structures, as well as the use of preservatives, is effective in storing flax retted straw of high moisture content. Although it should be noted that the use of this installation contributes to the preservation of physical and mechanical properties of flax raw materials but not for the entire storage period. Thus, for 30 days the physical and mechanical parameters of the retted straw remained at the proper level, at a sample moisture content of 25%, 35%, and at 45% there is a significant decrease, which does not meet the requirements of regulatory and technical documentation. For a longer period of 45; 60 days, the preservation of retted straw quality is observed only at the flax moisture content of 25%, and at other levels of moisture content there is an abrupt decrease in strength.

Comparison of the results of studies obtained using preservatives and the installation of hollow structures shows that the best effect of maintaining the quality of flax raw materials is achieved with the use of the aqueous solution of carbamide as preservative.

Since in the study on the storage of high moisture content flax retted straw, the best results were obtained with the use of carbamide, the mathematical model of the retted straw storage process was developed on the basis of experimental data using the specified preservative. The main indicator of the flax retted straw quality during storage is the breaking load, which characterizes the fiber strength, so this indicator was chosen as the initial criterion.

Based on the results of the study, a mathematical model of the retted straw storage process using an aqueous solution of carbamide was obtained in the form of a corresponding regression equation in coded and natural form, which allows determining the breaking load during the storage of flax retted straw of high moisture content:

The regression equation in natural variables is presented as follows (1):

$$P = 9{,}791 + 0{,}388C + 0{,}736T - 1{,}026W + 0{,}04CT + 0{,}265\ CW - 0{,}033TW - 0{,}377C^2 - 0{,}0015T^2 - 0{,}002W^2, \quad (1)$$

Where: P – breaking load, daN;

C – preservative concentration, %;

T – storage term, days;

W – moisture content in flax retted straw, %.

After obtaining a relevant model of the storage process of flax retted straw using an aqueous solution of carbamide, the response surfaces describing the storage process of high moisture content flax retted straw were investigated and the optimal values of the factors influencing this process were determined. For this purpose, graphical dependences of the strength of flax retted straw on the influence factors were developed. The shape of the surface was determined by the canonical equation to which the equation of the second-order polynomial describing this surface is reduced. Two-dimensional cross-sections were investigated to determine the type of response surface.

Based on the obtained mathematical model of the retted straw storage process, diagrams of the dependences of the breaking load on the concentration of carbamide solution, storage duration, moisture content of the flax retted straw were built, that are presented in Fig 4; 5; 6. Dependence diagrams are built in such a way that only one factor varies, the influence of which on the optimizing value is studied, and other factors remain at the basic level of variation. Fig. 4 shows how the retted straw strength changes with the variation of the preservative solution concentration, which is to ensure the storage of flax retted straw.

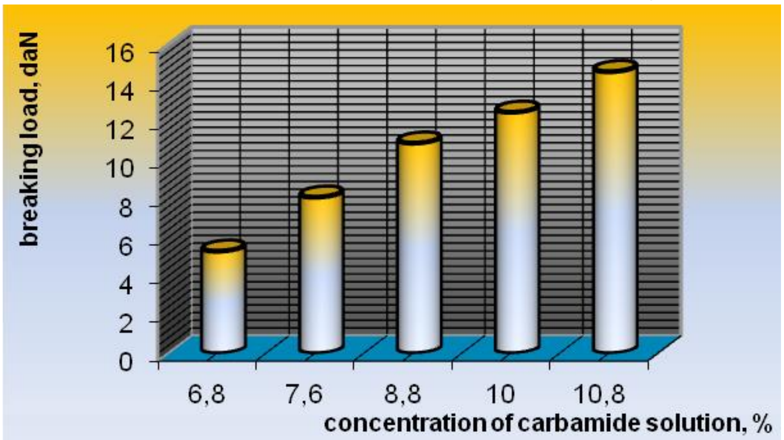

Fig. 4 - Dependence of strength of the high moisture content flax retted straw on the concentration of carbamide aqueous solution at T = 45 days; W = 30%

The diagram (Fig. 4) shows that the output parameter is directly dependent on the specified factor. As the concentration of the preservative increases, the probability of obtaining a fiber with the appropriate value of the strength index increases. Therefore, it is necessary to further determine the optimal value of a specified factor, at which it would be possible to ensure the storage of flax retted straw of high moisture content.

Fig. 5 shows how the retted straw strength changes with the changes in storage duration of flax retted straw of high moisture content. It is seen that within 30 days there is a rather sharp decrease in fiber strength, and in the next 30 days it stabilizes somewhat. After a period of 60 days of storage, the strength of the fiber again decreases quite rapidly. The diagram shows a short period of 30-45 days, during which the strength of the fiber is in a fairly stable state, i.e. it is possible to assume that these are the best storage conditions for flax retted straw under the influence of this factor.

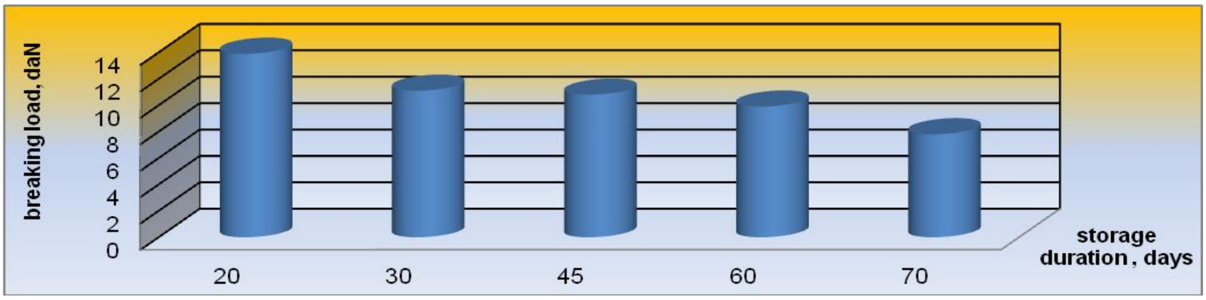

Fig. 5 - Dependence of the strength of flax retted straw on the storage duration at C = 8.8%; W = 30%

When superimposing two diagrams of dependences, it is possible to identify the optimal storage conditions of the flax retted straw of high moisture content under the action of the two above-mentioned influence factors. The most favorable conditions for obtaining fiber of high quality can be considered the preservative concentration C = 7÷9%; storage term T = 30÷45 days; moisture content W = 30%.

Fig. 6 shows how the retted straw strength changes with the changes in the moisture content of the flax material. Analysis of the diagram indicates that the initial parameter is inversely related to a specified factor, i.e. increasing moisture content of the flax material leads to the decrease in the strength of the fiber obtained by processing. Thus, it is necessary to further determine the optimal value of a specified factor at which it would be possible to ensure the storage of flax retted straw of high moisture content. On the diagram it is possible to allocate an interval at W = 25÷35% on which fiber strength values decrease not so rapidly, it is possible to consider this stage of changing moisture content in flax retted straw optimum.

The diagrams in Figs. 4; 5; 6 show that the flax fiber strength varies according to a certain law depending on the factors that influence it. As expected, the strength is significantly affected by all these factors, especially the preservative solution concentration and the moisture content in the material. It should be noted that when stabilizing the two factors at the main level, these dependencies are almost linear, which indicates the identity in the laws of change in fiber strength.

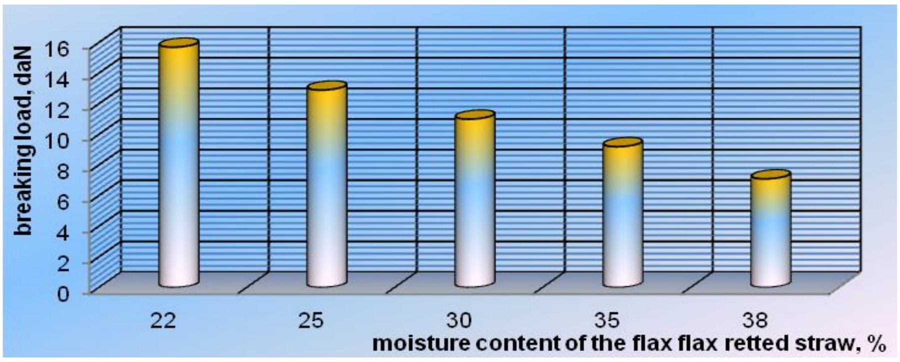

Fig. 6 - Dependence of the flax retted straw strength on the moisture content at C = 8.8%; T = 45 days

Graphs of one-dimensional cross-sections do not contradict the generally accepted provisions. Thus, when using a preservative aqueous carbamide solution of a higher concentration, the strength of the flax fiber will remain quite significant. With increasing storage term or moisture content in the material at other constant indicators of the influence factors, a decrease in the strength of the flax retted straw occurs.

For a more detailed consideration of the dependences of the retted straw strength on the carbamide solution concentration, the moisture content in flax retted straw, duration of storage, and determination of the optimal mode of storage technology of high moisture content retted straw, a two-dimensional cross-section of the response surfaces was used. The storage process of high moisture content retted straw when using an aqueous carbamide solution is characterized by hyperbola contour lines. According to the analysis of the response surfaces, it was found that the maximum values of flax retted straw moisture and the preservative solution concentration allow obtaining the minimum values of strength; the area of optimal strength ($y \to$max) is set at minimum values of moisture and insignificant values of preservative concentration. The hyperbola contour lines are descending.

From a practical point of view, increasing the concentration by more than 10% is not appropriate; therefore, the change in strength at the given concentration below C = 10% was verified. For a complete picture of the phenomena that occur during storage of flax retted straw of high moisture content with the use of carbamide, the effect of its aqueous solution on a constant concentration at the level of C = 7.6% was evaluated. Given the above, a study of the cross-section of the construction of hyperbola curved lines was carried out (Fig. 7).

According to the performed analysis, it was found that the hyperbola contour lines both under the constant factor of storage term (T) and the constant factor of the preservative solution concentration (C) are descending. Herewith, the range of optimal strength values at T = 45 days is set at minimum values of material moisture and insignificant values of preservative concentration, and at C = 7.6% and C = 10% - at maximum values of storage duration and material moisture.

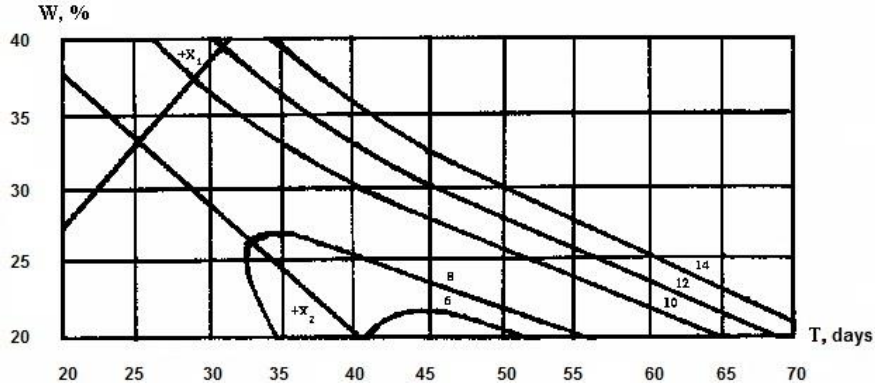

Fig. 7 - Two-dimensional cross-section of the response surface at C = 7.6%

Comparison of two-dimensional cross-sections allowed determining the optimal values of all influencing factors. In the study of the mathematical model in various storage modes, different types of two-dimensional cross-sections were obtained: when fixing the moisture factor and varying the other two, an ellipse was obtained, in other cases, the same values of input parameters resulted in a hyperbola. This made it possible to more deeply consider and imagine the course of processes, enabled to study the dependence of optimization parameters not only on the factors influencing the process but also on their interaction. The generalization of the experiment results, the analysis of one-dimensional and two-dimensional cross-sections gave grounds to assert that the process of storage of flax retted straw of high moisture content should take place under the following rational storage conditions:

- the moisture content of flax material should not exceed 35%;
- it is advisable to leave flax retted straw of high moisture content for storage for up to 45 days;
- to use a preservative aqueous solution of carbamide with a concentration range of 8.8-10%.

In the analysis of one-dimensional and two-dimensional cross-sections of the response surfaces of the mathematical storage process model of high-moisture flax retted straw, a certain variable regularity is observed in a specific change area of input parameters. It was established that the strength of flax fiber obtained by processing retted straw is linearly dependent on the concentration of the preservative aqueous solution, as well as on the moisture content of the material described by the empirical equations.

CONCLUSIONS

According to the results of scientific and theoretical research, it was determined that the most expedient and cost-effective way to store flax retted straw of high moisture content is the use of preservatives, such as an aqueous solution of carbamide. This is due to the fact that artificial drying of raw materials is not used in practice because of significant energy and material costs; the recommended technology is simple, reliable, and cheap, aqueous solution of carbamide as a preservative can ensure the quality of flax raw material at the appropriate level.

It was established that such preservatives as carbamide, ammonium nitrate, worked-out aethonium inhibit the activity of cellulose-destructive microorganisms, and thus ensure the preservation of physical and mechanical properties of flax retted straw. It was found that to obtain positive results of storing retted straw when using the technology of treatment of flax retted straw stems with carbamide, it is necessary to apply 150 ml of its preservative aqueous solution per 1 kg of flax material, which will ensure maximum irrigation of packaging and penetration of preservatives into stems.

When using a preservative solution of carbamide, it was found that the quality of flax retted straw remains high for up to 60 days. It was theoretically and experimentally proved that increasing the concentration of carbamide over 10% to maintain the quality of flax raw material is not feasible and thus irrational. The best results of preserving the quality of flax retted straw are achieved when using preservative solutions with a concentration of 8.8%, which can be considered as close as possible to the optimum value if the moisture content in flax material does not exceed 35% and storage term is 60 days.

It was found that the installation of hollow structures provides storage of flax retted straw of high moisture content, it is environmentally friendly and can present an alternative to the use of chemical preservatives.

REFERENCES

[1] Abbar, B., Alem A., Pantet A., Marcotte S., Ahfir N.-D., Duriatti D., (2017), Experimental investigation on removal of suspended particles from water using flax fiber geotextiles, *Environmental Technology*, V. 38, № 23, 2964-2978;

[2] Berezovsky, Yu.V., (2018), Technical solution for scutching the raw bast material (Технічні рішення процесу тіпання луб'яної сировини), *Science and innovation*, V. 14, № 1, 26-39;

[3] Berezovsky, Yu., Kuzmina, T., Lialina, N., Yedynovych, M., Lobov, O., (2020), Technical and technological solutions for producing fiber from bast crops, *INMATEH - Agricultural Engineering*. Vol. 60, №. 1, 137-146;

[4] Bobyr, S.V., Kuzmina, T.O., Rastorhueva, M.Y., (2014), Preservation of quality parameters of the straw of oil flax in the conditions of the southern of Ukraine (Сохранность качественных показателей соломы льна масличного в условиях юга Украины), *Vestnik of Vitebsk State Technological University,* № 26, 29-37;

[5] Boyarchenkova, M.M., Mareeva, Z.I., (1988), Use of chemicals as preservatives for wet flax raw material (Использование химических веществ в качестве консервантов влажного льносырья), *Breeding, seed production and agrotechnology of flax cultivation*, 167-170;

[6] Chursina, L.A., Berezovsky, Yu.V., (2002), *Ejector (Ежектор).* Ukraine, Patent, № 49617;

[7] Didukh, V.F., Dudarev, I.M., Kirchuk, R.V., (2008), *Harvesting and primary processing of flax (Збирання та первинна переробка льону-довгунця)*, Lutsk / Ukraine, "LNTU" Publishing House; ISBN 978-966-7667-84-9;

[8] Dudarev, I., Say, V., (2020), Development of resource-saving technology of linseed harvesting. *Journal of Natural Fibers*, 17 (9), 1307-1316;

[9] Gopu, R. Nair, Denis Rhoand, G.S., Vijaya Raghavan, (2013), Application of electro-technologies in processing of flax fiber. *Fibers*, 1 (2), 21-35;

[10] Grebennikov, V.S., (1990), Aliens in honeycombs (Инопланетяне в сотах), *Nature and man*, № 8, 22-27.

[11] Holovenko, T.N., Tikhosova, H.A., Bogdanova, O.F., Shovkomud, A.V., (2018), Analysis of the state of light industry in Ukraine (Анализ состояния легкой промышленности Украины), *Proceedings of higher educational institutions. Textile Industry Technology*, Issue 5 (377), 251-254;

[12] Khilevich, V.S., (1992), *Changes in the preservation of flax products during storage and measures to increase (Изменение сохраняемости льнопродукции при ее хранении и мероприятия по повышению)*. Kyiv / Ukraine, "UkrINTEI" Publishing House;

[13] Kuzmina, T.O., Yedynovych, M.B., Berezovsky, Yu.V., Bobyr, S.V., Yevtushenko, V.V., Rudenko, I.A., (2018), Application of biologically active substances to storage of oil flax straw (Застосування біологічно активних препаратів для зберігання соломи льону олійного), *Science and innovation*, V. 14, № 4, 26-39;

[14] Kyryliuk, R.M., (1994), *Changing the quality of flax raw material during cooking and storage (Зміна якості льонотрести в процесі приготування і її зберігання),* Ph.D. dissertation, Kyiv/Ukraine; Ukrainian State Agrarian University;

[15] Mankowski, J., Maksymiuk, W., Spychalski, G., Kolodziej, J., Kubacki, A., Kupka, D., Pudelko, K., (2018), Research on new technology of fiber flax harvesting. *Journal of Natural Fibers*, 15 (1), 53-61;

[16] Mukhin, V.V., (1985), Dosing with liquid chemical preservatives of flax in pressing of rolls (Дозирование жидких химических консервантов при прессовании льна в рулоны), *XXII International Symposium "Economy, mechanization and primary processing"*, Kyiv/Ukraine, 64-68;

[17] Ostrik, N.M., (1983), *Improvement of the technology of post-harvest processing and storage of flax raw materials (Усовершенствование технологии послеуборочной обработки и хранения льносырья)*, Ph.D. dissertation, Kyiv/Ukraine; Ukrainian Academy of Agricultural Sciences;
[18] Roland, J., Mosiniak, M., Roland, D., (1996), Dynamics of the cellulose microfibrils orientation in the cell wall of the flax fibers. *Acta Botanica Callica*; V. 142, № 5, 463-484;
[19] Semakov, V.V., (1994), Unconventional ways (Нетрадиционные способы), *Plant protection*, 3, 16-17;
[20] Yaheliuk, S., Didukh, V., Busnyuk, V., Boyko, G., Shubalyi, O., (2020), Optimization on efficient combustion process of small-sized fuel rolls made of oleaginous flax residues, *INMATEH - Agricultural Engineering*. V. 62, №. 3, 361-368;
[21] *** Demand for flax seeds is growing in Ukraine (В Україні зростає попит на насіння льону). *Agronews.Ua.* URL: https://agronews.ua/news/v-ukraini-zrostaie-popyt-na-nasinnia-lonu/. Last accessed: 10.02.2021);
[22] ***State Statistics Service of Ukraine, (2020), URL: http://www.ukrstat.gov.ua.