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Study of the strength of lignocellulosic raw material fibers with HWE using the example of hemp (*Cannabis sativa* L.) fibers

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Abstract: For technology development and adaptation to local needs, it may be necessary to modify lignocellulosic materials such as *Cannabis sativa* L. with appropriate methods and techniques. During the modification process, the lignocellulosic complex (LCC) of the raw material is interfered with to activate chemical compounds. After extraction, the research's most significant finding is that the post-extraction material has a lower tensile strength, which improves the conditions for its extraction. The entanglement of materials in harvesting equipment is a well-known problem, and any method that facilitates hemp harvesting is highly beneficial. The current study uses Hot Water Extraction (HWE) to characterize the hemp stalk before and after the extraction process. An analysis of the data will be conducted on the prepared samples after testing for strength. The study examines how the strength of raw materials varies depending on the degree of interference with the chemical composition and structure of the lignocellulosic complex (LCC).The main goal was to test the effect of different cycles of the HWE process on the strength of hemp fibers.

Keywords: lignocellulosic; Hot Water Extraction; HWE; hemp; fibers

INTRODUCTION

The modification of lignocellulosic materials through innovative methods offers a new approach to better manage plant materials in the future. Utilizing plant materials for sustainable development has numerous benefits and great potential. *Cannabis sativa*, commonly known as hemp, has been utilized for centuries for various purposes, including as a valuable source of plant fibers. Hemp is a valuable raw material for manufacturing lignocellulosic materials due to its significant quantities of fibers and lignin [Leszczyński, M.; Roman K. 2023]. These fibers, derived from hemp stems, are strong and can be used for various purposes, including textile production. Lignin, a type of fiber found in hemp, is used to make fabrics, papers, ropes, and other items. Hemp fibers are renowned for their durability and longevity, owed in part to the lignin present in their cell walls. Hemp fibers are renowned for their durability and longevity, owed in part to the lignin present in their cell walls. Hemp fibers are renowned for their durability and longevity, owed in part to the lignin present in their cell walls. Lignin, a complex organic polymer, is a crucial component of plant cell walls. The presence of lignin has a significant impact on the properties of lignocellulosic materials.

In Poland, the cultivation of hemp is legal as long as the varieties grown comply with legal guidelines. Hemp can be grown for industrial purposes, such as obtaining fibers, oils, and other products. This lignocellulosic material has a long history of cultivation in Poland. The use of hemp has recently gained attention due to its diverse applications. Various hemp varieties are adapted for fiber production depending on their intended use. Industrial plants process hemp fibers into textiles, ropes, and insulation. Additionally, paper and other products

are made from hemp varieties legally grown in Poland. Innovations in hemp processing can also impact new products. When deciding whether to grow hemp or use it, it is important to calculate the economic and environmental benefits of hemp or hemp lignocellulosic material.

Hemp is a versatile material with numerous applications in various fields, including traditional and innovative ones. Hemp fibers are used in construction materials such as hemp lightweight concrete and hemp panels due to their lightweight, strong, and excellent insulation properties. Natural hemp fibers can be combined with thermoplastics to create biocomposites [Leszczyński, M.; Roman K. 2023; Patel, N.; Feofilovs, M.; Blumberga, D.2022]. Biocomposites are materials made by blending natural fibers with polymers. Hemp biocomposites can be used as an alternative to various structural components and consumer products due to their versatility. They are environmentally friendly and can be used to produce eco-friendly fabrics and packaging, making them an ideal substitute for plastic packaging. In addition to its use in biofuel production, hemp has also been utilized in innovative ways. Hemp oil can be used to produce biodiesel, and the leftover residue can be used as biomass for energy production.

While there are a number of areas where hemp can be used, these examples illustrate that hemp is a versatile raw material that can be used in both traditional and innovative ways. As technology advances and environmental awareness increases, innovations in hemp use will continue to develop. Several studies have assessed the biodegradability of hemp seed products, demonstrating that their lignocellulosic nature is one of their main advantages. This characteristic makes hemp products more eco-friendly than other alternatives, reducing their environmental impact. The utilization of hemp as a lignocellulosic raw material can be optimized for various agricultural applications, promoting sustainable management of natural resources in an environmentally superior manner compared to other raw materials, including hemp.

MATERIALS AND METHODS

Material

Hemp fibers can be extracted from the stalks and stems of *Cannabis sativa* L. plants. Similarly, long and strong strings can be extracted from the skins of various types of globe beans. Hemp fibers are known for their flexibility and durability, which is due to their length. The physical properties of hemp fiber are determined by various elements in its structure. Hemp fibers are composed of several key elements, with strength and elasticity deriving from cellulose, the primary component of this fiber. The fiber's exterior is mainly composed of cellulose, hemicellulose, and lignin, which are the building blocks of the cell wall. Typically, 70-80% of this product's content is natural. Cellulose provides strength, elasticity, and structural integrity to fibers, while lignin provides structural integrity. Natural hemp fibers come in various shades of brown, gray, and green, giving them a unique appearance and enhancing their natural appeal.

The strength of hemp fibers comes from microfibrils, which are microscopic threads of cellulose that run along the fiber's axis. Plant cells contain numerous water channels that help maintain moisture balance, leading to the formation of short-circuit cells and crystal clusters that affect the cells' physical properties. Hemp seed fiber's structure enables its use in various applications, including textiles and building materials. Plant fibers contain organic substances, such as lignin, that strengthen their cells and structures. Hemicellulose, which is present alongside cellulose, improves elasticity. Pectin and wax affect adhesion and moisture resistance, which in turn affect the physical properties of fibers. There is no doubt that some varieties of hemp contain cannabinoids such as CBD. However, in the context of the fibers

made from hemp plants, the amounts of these compounds are generally quite low. This chemical composition makes hemp fibers an attractive raw material for textiles, paper, construction, and the automotive industry, among others.

Hot Water Extraction - Samples preparation

The raw lignocellulose material had to be pre-treated prior to processing for tensile purposes according to the concepts developed in this study. The material processing stages were divided systematically to ensure the research project's framework was followed. The process involved preprocessing and pretreating the lignocellulose raw material. This approach allowed for an efficient and systematic completion of the study. The study utilized a pretreatment process on hemp stalks (*Cannabis sativa* L.) to test their tensile strength. The research material underwent a basic research series, starting with a native test and then analyzed after modification. Hot Water Extraction (HWE) is a crucial step in the process that can significantly improve efficiency. To extract, 10g fibers of raw material were placed into a container, and 400g of distilled water was used for the extraction process. The aperture used for Hot Water Extraction is shown in Figure 1.

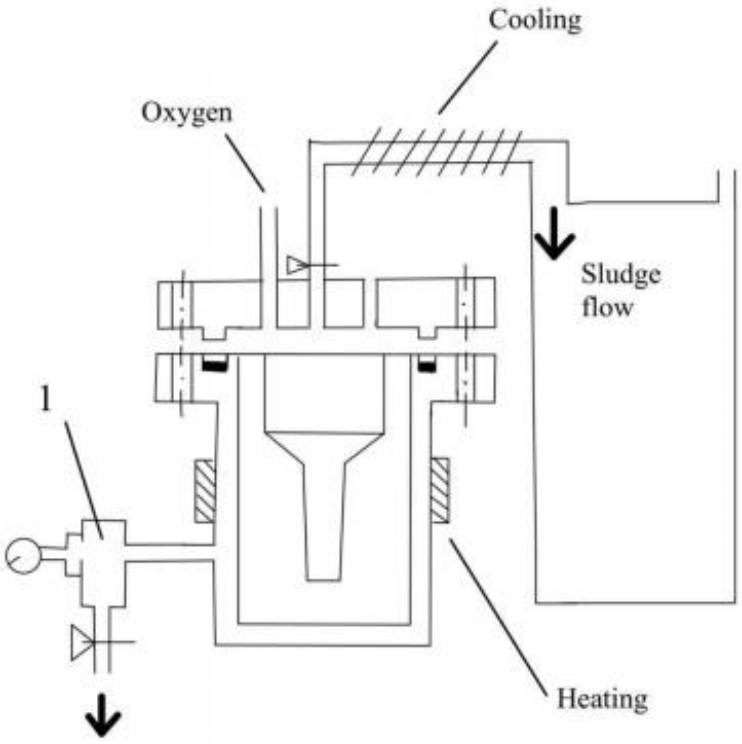


Figure 1. The aperture used for Hot Water Extraction.

In order to extract hydrocarbons, the Hot Water Extraction (HWE) process is performed at a temperature of 100°C and a pressure of 2 MPa. The extraction process was repeated three times in a row, each time taking about 30 minutes. It was used a cylindrical device in order to carry out the HWE process in order to make it as efficient as possible. It was decided that the main parts would be placed at the bottom of the reactor, into which distilled water would be poured each time it was used. It was placed at the top of the reactor, a container containing the raw material that would be going through the HWE process. There is a tube located in the middle of the container that extends towards the bottom of the container. The top portion of the material was equipped with a lid that had a hole on it for pressure drainage in order to extract the desolated water that has gone through it in as much quantity as possible. The raw material could then be effectively and efficiently processed through the use of this process.

Material Moisture Measurement

The initial step in the testing procedure for maintaining moisture content in a test material involves drying it to the point of dryness in a laboratory dryer at 105°C. To standardize the moisture content measurement of all samples, they must be placed in a laboratory cuvette specifically designed for measuring moisture content. It is necessary to repeat the treatment after two weeks to maintain a moisture content of 12%. To determine the moisture content of samples, a laboratory cuvette with a medium is calibrated. Environmental factors, such as temperature and humidity levels, can affect the values in the cuvette. The weight of the samples should be measured before each test to verify their moisture content. The study utilized PN-ISO 589:2006 guidelines to determine the moisture percentage of lignocellulosic samples. The moisture content of each sample was verified prior to conducting the tensile test. A Radwag MAC 50 weighing machine (Radom, Poland) was used to measure the weight of the cut-off material.

Optical analyze

The optical analysis of samples under the microscope entails several key steps in order to be able to study in greater detail the structural characteristics and microscopic features of the lignocellulosic materials. In the first stage of the study, the nature of the material under investigation required that the sample be prepared by sectioning in order to be examined. Optical analysis of the sample was possible through the use of the type of microscope that was chosen at the desired resolution using optical imaging. As part of a tuning process, an external light source provided by an integrated amplifier was used to support the microscope. In order to obtain an image of the sample during the analysis, a digital camera was used to capture the image of the sample. This optical analysis was carried out using the Nikon SMZ 1500 microscope as well as the computer program for data analysis in order to determine the optical characteristics. Various additional filters were used to enhance the image or identify specific features of the image in order to eliminate contrast issues and correct the image.

Analyses of images were conducted by evaluating the morphology, taking measurements of the dimensions, and identifying structural characteristics. In this stereoscopic microscope, the zoom range is 15:1 and the zoom range can be adjusted from 0.75 to 112.5. It is therefore possible to see samples from macro views to high-magnification micro visualization, all in the same device. An optical system for the microscope has been designed with the intention to correct both planar and axial chromatic aberrations of the images. There is a halogen illuminator in the microscope with an output of 150 watts. After the images had been obtained, the results were compared among themselves to characterize the known and deviated structures that have been used as standards for identifying and characterizing samples. An effective optical analysis of samples under microscopes can be achieved by carefully interpreting the results and maintaining appropriate documentation, therefore providing a comprehensive understanding of the structure and properties of the materials under study.

Tensile Testing

The tensile test is the most commonly used test for determining the mechanical properties of materials. In tensile testing, static tensions are tested for their ability to resist the tension forces applied to them when they are in contact with each other. The material is subjected to a constant tensile load during this type of test, and its strength is measured as a result. Under these conditions, it is important to evaluate whether the structure will be able to maintain structural integrity. An integral sensor monitored the stretching of the material uniaxially, uniformly, and in a controlled manner. Static tensile testing is a test that gradually deforms the material through the application of tension. The primary parameters evaluated in this test are the tensile strength and the elongation of the material.

The purpose of the test is to determine the characteristics of the specimen that can be used to determine the tensile strength, flow stress, and strain energy of the specimen. In accordance with ISO 527-1, the tensile test of the fabric was conducted in a controlled environment. To determine the strength of the modified hemp, it was necessary to conduct tensile tests along the fibers in order to determine its strength along the fibers as well as along the material itself. A study was conducted in this study in order to determine the effectiveness of Hamp (*Cannabis sativa* L). There was a different shape for each sample as well as the type of material that was individually prepared. There was a difference in cross-side dimension between every lease of the sample. There was a standardization of the moisture content of the samples before they were tested [3]. The tensile strength of the fibers was tested in the laboratory using a machine manufactured by Instron (Norwood, MA, USA) that measures fiber tensile strength. In order to perform the tensile test, a clamping fixture was installed. Several instruments were used for the testing of tensile strength, including tensile test clamps, measuring computers, Instrom IX software and a testing machine. During the static tensile test, the specimen was considered to have finished when it was completely ripped in half after being subjected to the test.

The tensile test is one of the most basic ways of determining the mechanical properties of a material [Murata, K.; Nagai, H.; Nakano, T.2011; Östman, B.A..-L.1985]. The purpose of this test is to measure the amount of force necessary to pull apart a material, which is useful for determining the strength and stiffness of that material. The test results can also provide information regarding how much stress and strain is present in the material during the test. The test procedure involves determining the characteristics of the material under tension and then carrying out the test procedure on it after it has been characterized. There is also the possibility that, during the process of analyzing the specimen, parameters of the material can also be determined which contribute to the amount of deformation that is experienced by the specimen. In accordance with the specifications of the manufacturer, various tensile tests were conducted according to the standard [Östman, B.A..-L.1985]. Material properties such as tensile strength and elasticity modulus were determined using the results of tests.

RESULTS

Material

The fibers from hemp (*Cannabis sativa* L.) are a valuable natural resource [Altman, A.W.; Kent-Dennis, C.; Klotz, J.L.; McLeod, K.R.; Vanzant, E.S.; Harmon, D.L. 2024]. The scientific literature shows that hemp seed fibers are among the earliest plant fibers [Song, H.; Liu, T.; Gauvin, F. 2024]. Fibers from the stems of the plants have unique properties that make them attractive to a variety of industries [Altman, A.W.; Kent-Dennis, C.; Klotz, J.L.; McLeod, K.R.; Vanzant, E.S.; Harmon, D.L. 2024; Song, H.; Liu, T.; Gauvin, F. 2024]. In addition to their high strength and tear resistance, hemp fibers are also very elastic, making them an excellent material for the production of durable fabrics, thanks to their low degradation rate. Moreover, they are lightweight and have thermoregulatory properties, which makes them very convenient to wear and they are also very comfortable. Several studies have also shown that hemp seeds have the potential to have environmental benefits, as they require less pesticides and herbicides than some traditional fiber crops that are grown [Altman, A.W.; Kent-Dennis, C.; Klotz, J.L.; McLeod, K.R.; Vanzant, E.S.; Harmon, D.L. 2024; Nowakowski-Pałka, J.; Roman, K 2023].

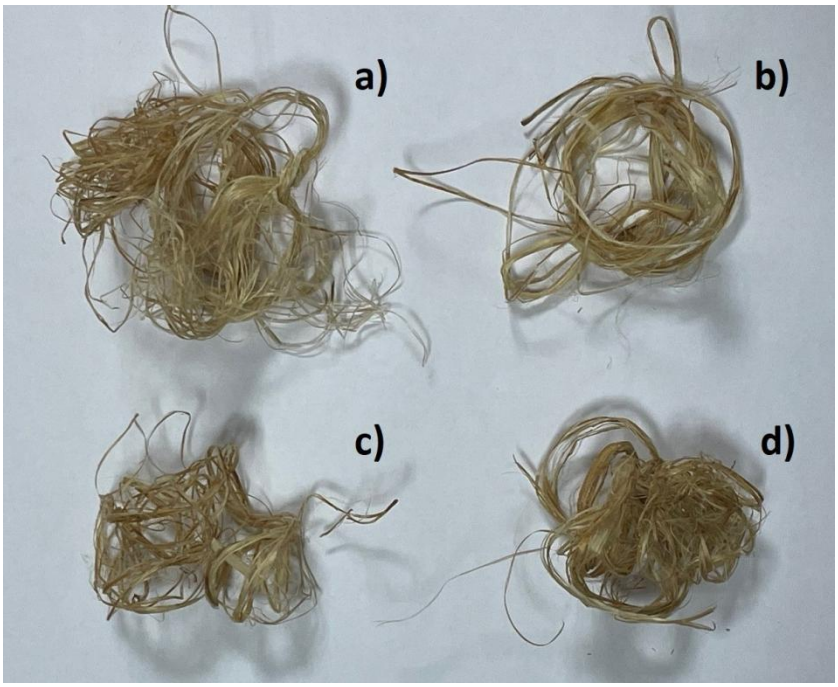


Figure 3. The hemp samples: a)Native; b)HWE I; c)HWEII; d) HWEIII.

The potential for hemp to be used in the production of organic [Leszczyński, M.; Roman, K. 2023] and sustainable products [Altman, A.W.; Kent-Dennis, C.; Klotz, J.L.; McLeod, K.R.; Vanzant, E.S.; Harmon, D.L. 2024] has fueled a growing interest in the plant. As a result of the potential applications that these plants have, they have become widely popular in recent years. Researchers have also investigated the chemistry of seed hemp fibers in order to identify and modify chemicals within the fibers that can improve their technical properties and make them more suitable for different application areas, such as cellulose and lignin, in order to enhance their technical properties. Hemp fibers represent a fascinating area of research, and the possibility of using hemp fibers for textiles, building materials, and even biocomposites is still being explored in the laboratory through intensive scientific research, resulting in new opportunities for industries and the environment. There is no doubt that hemp fibers have a great deal of potential to revolutionize numerous industries in the future as well as help us move towards a more sustainable future. The comparison of fiber weight at different stages of the HWE process were presented in Table 1.

Table 1. The comparison of fiber weight at different stages of the HWE process.

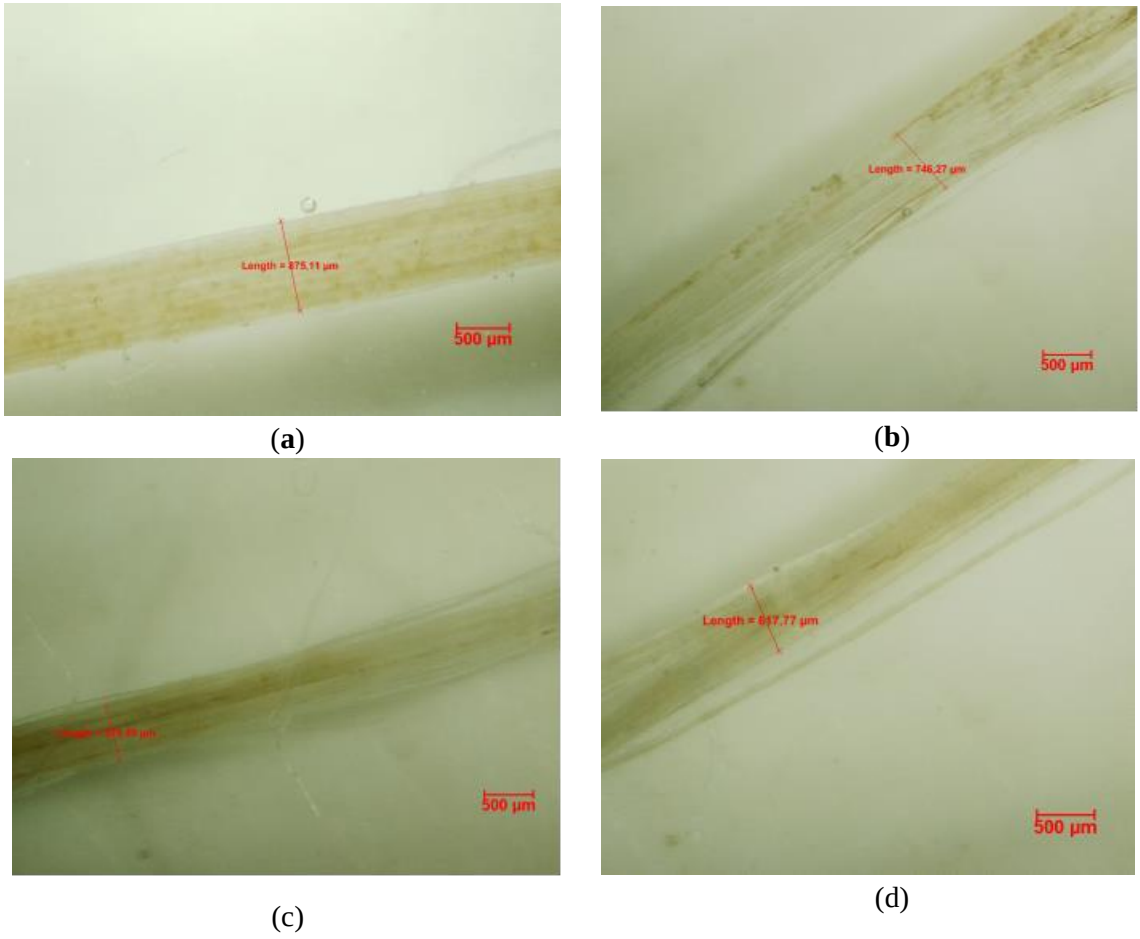
Number of the HWE Process	Absolute Dry Fibers Weight [g]	Wet Fibers Weight [g]	Wet Fibers Weight after HWE [g]
I	5,8	-	17,5
II-1	4,4	-	11,8
II-2	-	11,8	12,1
III-1	4,2	-	12,3
III-2	-	12,3	12,2
III-3	-	12,2	12,4

The table above shows a comparison of the weights of fibers before and after the HWE process as well as the weights after the extraction process at different stages during the process. The dry fiber mass in HWE I was 5.8g, and after the process it increased to 17.5g. This was

followed by an increase of 4.4g to 11.8g in HWE II-1 sample, and 0.3g by HWE II-2 to 12.1g that overall difference was 7.7g. The result after the HWE III extraction process, the fiber mass increased from 4.2g to 12.3g. During the HWE III-2 process, for unknown reasons, the mass of the fibers decreased by 0.1g, giving an overall difference of 12.2g. At the next HWE III-3 process, the fiber mass increased slightly to 12.4g (an overall difference of 8.2g). A total increase of 11.7 grams in fiber mass was obtained in the HWE I process, when a difference of 11.7 grams was observed. During the HWE II process, the smallest weight gain occurred in HWE II, where the difference was 7.7g. The average gain we received within the HWE III process was 8.2g.

Optical analyze

The optical analysis of the hemp stalk taken under a microscope provides important information about its structure and composition, as well as its pesticide content. It is possible to observe different tissue types on a seed hemp stalk using a microscope, which is helpful in identifying key characteristics of morphology through close examination. In microscopic examinations of hemp sclerenchyma cells, conducting vessels, fibers, and covering tissues may be identified. Stability and potential industrial applications of these structures are both important for the plant. Based on the prepared optical analysis of the hemp stalk, a comparison is shown between the native material as well as the raw material after the HWE process is carried out on the stalk. The cross-sections of the hemp fibres for native material and material after HWE was presented in Figure 3.



(**a**) (**b**)

(c) (d)

Figure 2. The cross-sections of the hemp fibres: (**a**) Native; (**b**) HWE I; (**a**) HWEII; (**d**) HWE III.

The extraordinary strength of hemp fibers makes them an ideal raw material for the production of stress transfer materials as a result of their use as raw materials. Microscopy provides a means of identifying and analyzing cannabinoid glands on stalks of raw materials. It is possible to determine the potential cannabinoid content of a given plant material under a microscope by studying these glands under the microscope. In order to understand its structure, chemical composition, and potential applications in various fields, including the textile industry, optical analysis of the hemp seed stalk under the microscope is a key component of morphological and chemical analysis of the plant. Furthermore, a steam pressure of 2 bar is used to act on the biomass to activate the lignin and partially remove extractives and hemicelluloses. This results in the structure of the biomass being activated. In order to manipulate the raw material at about 100 °C, steam was applied to the raw material to help it warm up. In order to statistically determine the correlations between selected parameters, the native test was crucial for the statistical ascertainment of the correlations. The sample measurements of cross-sections of the hemp fibres were presented in Table 1.

Unmodified native hemp fibers can differ in transverse dimensions slightly from modified hemp fibers. There are 883.03µm on average, with 891.32µm being the maximum value and 875.11µm being the minimum. Taking these dimensions together, the standard deviation is 6.62µm. In addition, the largest value in HWE I was 746.27µm, while the smallest was 519.72µm. In this process, the cross sections averaged 649.34µm. The standard deviation was 95.33µm. The largest dimension after HWE II was 694.15µm, the smallest at 564.07 m, and the average was 612.57µm. There is a standard deviation of 58.03µm in the distribution.

Table 2. The cross-sections of the hemp fibres.

Cycle	Zoom, µm	Cross-section dimensions of one fiber, µm	Cross-section average dimensions of one fiber, µm
Native	500	882.66	883.03
		875.11	
		891.32	
HWE I	500	519.72	649,34
		746.27	
		682.04	
HWE II	500	564.07	612.57
		579.49	
		694.15	
HWE III	500	617.77	717.56
		716.29	
		818.63	

The largest dimension in HWE II is the highest dimension in HWE III, and the smallest dimension in HWE II is the highest dimension in HWE II. The transverse dimensions range from 617.77µm to 818.63µm. Considering these results, we can estimate that the average amount is of 717.56µm. There was an average standard deviation of 82µm. According to a comparison of all the above-mentioned processes, HWE significantly affects hemp fibers' transverse dimensions. The highest standard deviation was found in samples after HWE I at 95.33µm, while the lowest was found in unmodified samples at 6.62µm, based on comparison of fiber weights at different stages of process.

Energy consumption during the tensile process

The findings of the tensile test indicate that according to the modification applied to the tensile test specimens, the specimens of the tensile test had an entirely different course of change than those that were not modified. The static tensile test was conducted according to the protocol specified in the methodology. The forces applied to the specimens during the tensile process were measured in order to determine how much the specimens deformed as a result of the tensile process. An anisotropic structure of the lignocellulosic material appears to be responsible for the variation in the course of the tensile process that can be observed in lignocellulosic materials. The linearity of the curve was also distorted during the static tensile tests for each of the samples. The distortions that appear to be caused by cracks within the anisotropic structure of this material could have been caused by cracks within the material itself as well. Mechanical properties can also be affected by this anisotropic structure due to its anisotropy. In order to gain a better understanding of how the structure of the lignocellulosic material influences the tensile process, the research is in progress.

Static tensile tests are used in materials engineering to characterize material properties. The static tensile test measures material strength, stiffness, stretch, and deformation. Test results are crucial to the development of structural designs, material production, and safety analysis of structures. A static tensile test was conducted in order to ensure that the results of the static tensile test were in accordance with the applicable norms, and this was verified by the static tensile test conducted in accordance with the standard. Dimensions and properties of the sample materials were measured and tested. In order to determine a specimen's tensile strength, its cross-sectional area is divided by its maximum load and the result is the specimen's tensile strength. Material strength and stiffness were both determined by the results, which met the objective. The data was then used to assess the safety of the proposed design. Performing these tests is essential to the success of a structural design or manufacturing process. There was a constant speed of movement of the handle of the testing machine throughout the test, corresponding to a variable rate of v = 5 mm·s^{-1}. The characteristics of hemp's tensile process and its modification by HWE in regards to its tensile process are presented in Figure 1.

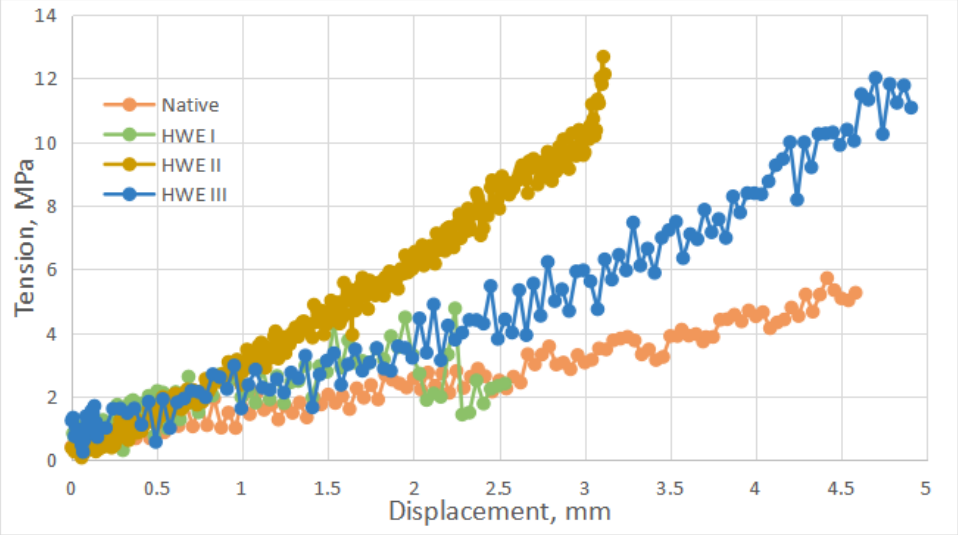


Figure 3. The characteristics of a tensile process for pine wood.

The manner in which force changed with displacement was characteristic of all the samples. The results of the tests were used to estimate the amount of energy needed for static stretching based on the results of the tests. The amount of energy required to tear a specimen should be calculated based on the grade and preparation parameters. For the purpose of the

calculation of the model, the Gauss-Newton least squares method was applied. The graph was used to calculate the coefficient of determination R2, which for a particular model had to be greater than 0.9. The assumption was that a coefficient no lower than 0.92 could be used to construct the polynomial according to the model. The method was required to be accurate enough to be able to factor the results into the model, otherwise, the procedure could not be considered successful. The polynomial of the third degree fits well with the arithmetic function that describes the stretching process of different samples. The integral equations for the total work of stretching are presented in Table 2.

According to the determination coefficient of the polynomial in the second degree, it shows the validity of using it to describe the forces which arise in the process of understanding the changes that take place. In accordance with the methodology of selecting the polynomial according to the determination coefficient, we were able to increase the accuracy of fitting the function defining the tensile process by following the methodology. There has been one instance in which the R2 has remained about 0.90, despite the use of a polynomial of the fourth degree in the calculation.

The trend line was still fitted with a polynomial of the second degree, however, if the R2 coefficient reached 0.95 or greater, the trend line was still fitted with a polynomial of the second degree.

Table 3. The integral equations for the total work of stretching.

Total Work Carried Out under Specified Conditions $W_{(\tau,\varphi)}$	**Determination Coefficient R^2**	**Displacement l, mm**	**Total Compaction Work, J**
$W_{(Native,I)} = \int_0^{0.001\cdot l} 0.2546x^2 + 0.968x$	0.9844	7.617	2.8×10^{-5}
$W_{(Native,II)} = \int_0^{0.001\cdot l} -0.0239x^2 + 1.1377x$	0,9736	8,125	3.8×10^{-5}
$W_{(Native,III)} = \int_0^{0.001\cdot l} 0.2628x^2 - 1.2462x$	0,954	16,583	17.2×10^{-5}
$W_{(HWE\ I,I)} = \int_0^{0.001\cdot l} 0.1477x^2 + 0.8799x$	0,9557	9,042	3.6×10^{-5}
$W_{(HWE\ I,II)} = \int_0^{0.001\cdot l} 0.5744x^2 + 1.3071x$	0,9942	4,700	1.4×10^{-5}
$W_{(HWE\ I,III)} = \int_0^{0.001\cdot l} 1.0438x^2 - 2.918x$	0,9723	10,575	16.3×10^{-5}
$W_{(HWE\ II,I)} = \int_0^{0.001\cdot l} 0.0182x^2 + 0.7296x$	0,9793	9,108	3.0×10^{-5}
$W_{(HWE\ II,II)} = \int_0^{0.001\cdot l} -0.0363x^4 + 0.4313x^3 - 1.608x^2 + 2.9678x$	0,9007	5,375	4.3×10^{-5}
$W_{(HWE\ II,III)} = \int_0^{0.001\cdot l} 0.2476x^2 + 2.6817x$	0,9878	3,117	1.3×10^{-5}
$W_{(HWE\ III,I)} = \int_0^{0.001\cdot l} 0.7638x^2 + 2.4127x$	0,9802	6,808	5.6×10^{-5}
$W_{(HWE\ III,II)} = \int_0^{0.001\cdot l} 1.0611x^2 + 0.7501x$	0,9936	5,275	1.0×10^{-5}
$W_{(HWE\ III,III)} = \int_0^{0.001\cdot l} 0{,}5587x^2 - 0{,}2593x$	0,9916	10,117	1.3×10^{-5}

The total work of the process was calculated according to the variation of the tensil force over time for different native and modified materials, based on the value of the tensil force

variation over time. In spite of the fact that the model is multinomial in nature, it may be possible to use it to accurately predict the amount of effort that will be put into the entire project as a result of its multinomial nature.

DISCUSSION

In the course of the study, conducted observations on two kinds of changes in hemp fibre weight: those that occurred before and those that occurred after the HWE process. It was revealed that significant changes in raw material mass were seen at various stages in the HWE process as a result of the analysis of fiber weights. It was interesting to note that the greatest difference in the fiber mass occurred after the HWE I process, as there was a difference of 11.7g in fiber mass after the HWE I process. While HWE II produces a smaller increase of 7.7g, it is still a significant increase. It was found that the mass of the fiber increased by 8.2 grams during the HWE III process. It may be necessary to further investigate the process to determine what caused the sudden decrease in fiber mass during HWE III-2. It may also be possible to suggest that there may be significant differences in the impacts of individual HWE stages.

In the course of our research, we completed an analysis of the optical fibres as one of our subsequent studies as part of our project. According to a study of the cross-sectional dimensions of hemp fibers, the average cross-sectional dimension of unmodified hemp fibers is 883.03 μm based on a study of the cross-sectional dimensions. It is evident that something had changed after HWE I, since the maximum length reached 746.27 μm and the standard deviation reached 95.33μm. HWE II represented an average dimension of 612.57 μm, with a standard deviation of 58.03. The dimensions after HWE III ranged between 617.77 μm and 818.63 μm, with an average dimension of 717.56 μm and a standard deviation of 82.00. Comparing processes, HWE significantly influences hemp fiber cross-sectional dimensions, especially after HWE I. The standard deviation of an unmodified sample is 6.62, while the standard deviation of a modified sample is 95.33. This analysis emphasizes the fact that fiber structure has changed dramatically, and has implications both for industry and further research in this field.

The last part of our research was the strength test, which was examined. Based on our analysis of the second-degree polynomial's determination coefficient in the current study, it can be concluded that this polynomial is a suitable method for describing forces associated with dynamic changes in a process under various dynamic conditions. The method of selecting a polynomial based on the coefficient of determination enhanced the precision of the function defining tensile process. In spite of the attempts to fit the trend line with a fourth-degree polynomial, the R^2 coefficient maintained around 0.90 in one instance, requiring the remaining trend line to be fitted with a second-degree polynomial. In order to establish its effectiveness, the R^2 coefficient had to reach 0.95 or higher. To calculate the total work involved in the process, the variation in tensile force over time for different native and modified materials had to be taken into account in calculating the total work involved in the process. This model has the property that along with its polynomial nature, it can be used to accurately predict the effort that will be needed throughout the entire project range despite its polynomial nature. Modeling effort and optimizing precision is an important part of the study, emphasizing the importance of the polynomial selected for foreseeing effort requirements at various stages of work.

CONCLUSIONS

The results of the research and the analysis of them can be used to draw several conclusions and comments. A significant difference of 11.7g was observed between HWE I and HWE II and III samples. The increases in HWE II and HWE III samples were slightly

lower, at 7.7g and 8.2, respectively. Based on microscopic examination of the hemp stalks, as well as statistical analysis, it was found that there were notable differences in transverse dimensions among the hemp stalks, inferring that HWE played a significant role in shaping hemp fibre properties and providing some indications as to why hemp fibre could be useful in various industries. Furthermore, the modification applied to the specimens during tensile tests affected their evolution significantly when compared to unmodified specimens, which clearly demonstrated the influence of the modification. Additionally, cellulose can be readily available in the material. As a result of hydrolysis, the remaining polysaccharides in the lignocelulosic material can be converted to simple sugars, which can then be fermented into ethanol. This raw material is fully renewable, being intended for use in the production of goods and services of positive value, and so its use for its intended purposes is ecologically and economically justified.

Research on the strength of lignocellulosic fibres from plant material utilizing high-temperature extraction, using hemp (*Cannabis sativa* L.) fibres as an example, may involve a number of research directions. This study aims to optimize HWE processes by experimenting with different conditions, such as temperature, time, and active ingredient concentrations, to identify the optimum conditions. Electron microscopy and micromechanical strength tests can be used to analyze hemp fiber microstructure after HWE and to determine how structural changes affect mechanical properties. By comparing the chemical composition of a sample before and after HWE, we can identify which chemical compounds were removed or modified. Researchers can also focus on evaluating the suitability of modified hemp fibres for the production of composites, biomaterials, and other sophisticated materials, which can be examined through innovative processing techniques. Green chemistry combined with the discovery of new sources of lignocellulose may be able to minimize the environmental impact of the HWE process. To maximize the efficiency of the recycling process, modified hemp fibres are being researched. It is necessary to investigate the properties of hemp fibre in relation to the conditions in which it grows. It is imperative to consider factors such as soil type, sunshine exposure, and climate in order to determine the quality of fibre. The integration of these research areas can enhance the understanding of hemp fibres and their potential application in industry and the environment.

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Streszczenie: W celu rozwoju technologii i dostosowania jej do lokalnych potrzeb, konieczna może być modyfikacja materiałów lignocelulozowych, takich jak *Cannabis sativa* L., za pomocą odpowiednich metod i technik. Podczas procesu modyfikacji dochodzi do interakcji z kompleksem lignocelulozowym (LCC) surowca w celu aktywacji związków chemicznych. Najważniejszym odkryciem badawczym jest to, że materiał poekstrakcyjny ma niższą wytrzymałość na rozciąganie, co poprawia warunki jego ekstrakcji. Zaplątywanie się materiałów w sprzęcie do zbioru jest dobrze znanym problemem, a każda metoda ułatwiająca zbiór konopi jest bardzo korzystna. Obecne badanie wykorzystuje ekstrakcję gorącą wodą (HWE) do scharakteryzowania łodygi konopi przed i po procesie ekstrakcji. Analiza danych zostanie przeprowadzona na przygotowanych próbkach po przetestowaniu ich wytrzymałości. Badanie sprawdza, w jaki sposób wytrzymałość surowców zmienia się w zależności od stopnia ingerencji w skład chemiczny i strukturę kompleksu lignocelulozowego (LCC). Głównym celem było przetestowanie wpływu różnych cykli procesu HWE na wytrzymałość włókien konopi.

Słowa kluczowe: lignocelulozowe; ekstrakcja gorącą wodą; HWE; konopie; włókna

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