

## Article

# Physico-Mechanical Properties of Male and Female Hemp Plants

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**Abstract:** Hemp (*Cannabis sativa* L.) is one of the oldest annual fiber crops cultivated throughout human history. Addressing the challenges encountered during the harvesting of hemp for seed and fiber purposes requires further investigation. Studies are also needed to determine plant characteristics in terms of both variety and gender. This study aimed to determine the physico-mechanical properties of hemp plants. The stems of male and female hemp plants were divided into three sections along their length: lower, middle, and upper regions. Samples measuring 25.4 mm in length were collected from each section, and measurements of thickness and inner and outer diameter were conducted. The same samples were subjected to axial and lateral compression tests to determine load, elongation, and energy values. According to the results, the thickness of hemp ranged from 2.347 mm to 2.628 mm, the inner diameter varied between 3.986 mm and 4.452 mm, while the outer diameter ranged from 8.861 mm to 9.708 mm. The results showed that male hemp plants have an increase in thickness and inner and outer diameter values from the lower to the upper region compared to female hemp plants. The compressive loads in the axial and lateral directions were found to be higher in male hemp plants compared to female hemp plants. Moreover, elongation and energy requirements during axial and lateral compressions showed trends consistent with the load values across the stem samples. This study determined that the results of axial and lateral compression applied at three different positions (lower, middle, and upper) on male and female hemp stalks varied significantly based on both sex and position.

**Keywords:** male and female hemp; physico-mechanical properties; compression stress; load



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## 1. Introduction

Hemp (*Cannabis sativa* L.), an annual crop from the Cannabaceae family, is among the oldest fiber plants humans cultivate. Native to Central Asia, hemp has been widely cultivated across the globe over the past 10,000 years [1]. The scientific and industrial importance of hemp as a renewable and sustainable resource continues to grow steadily [2]. Notably, all parts of the hemp plant are utilized in diverse ways across various industries, particularly in the fields of manufacturing and textiles. Furthermore, hemp serves as a vital raw material for a broad spectrum of products, including clothing, ropes, household goods, industrial oils, cosmetics, food items, and medicines [3,4]. All parts of the hemp plant, including stalks, seeds, leaves, and flowers, are utilized across various industries [5,6]. Moreover, in recent years, hemp has gained significance as a renewable raw material for producing strong, lightweight composite materials. Additionally, the cultivation of medical hemp in controlled environments has been on the rise due to advancements in healthcare applications [7]. Hemp fiber is also a valuable product for producing environmentally friendly and biodegradable products [8]. When compared to other natural fibers, such

as cotton, and petroleum-derived synthetic fibers, hemp stands out due to its superior ecological characteristics and significant potential for organic production [9].

The labor-intensive nature of hemp cultivation, combined with the presence of naturally occurring tetrahydrocannabinol (THC), has led many producers to shift toward alternative crops. Additionally, hemp has lost its competitive edge against cotton and synthetic fibers, contributing to a decline in cultivation areas. However, recent studies have highlighted the significant nutritional, economic, and social importance of hemp for humans [10,11]. Moreover, further research is necessary to fully unlock the potential of the hemp plant [12].

From an industrial perspective, hemp serves as the raw material for approximately 25,000 different products, with its market value expected to exceed 26.6 billion USD by 2025 [13]. The growing interest in hemp as a source of eco-friendly natural products has led to a significant increase in cultivation areas. Furthermore, since 2000, the use of industrial hemp fiber in the apparel industry has been steadily rising, contributing to the ongoing expansion of hemp cultivation [14]. However, further agricultural research is urgently needed to enhance profitability and productivity in hemp production [15].

Hemp is cultivated to obtain fiber and seeds, and its ultimate use determines the cultivation method. For fiber production, denser planting with higher plant density is employed, while for seed production, sparser planting is preferred [16]. This distinction highlights the necessity of considering these parameters during harvesting. Indeed, the mechanization of seed harvesting in hemp is crucial, as it significantly reduces production costs, including those for energy and seed inputs [17]. After harvest, several methods are used to separate the fibers from the stalks, including mechanical separation, retting, pooling, chemical treatments, and enzymatic processes.

The cultivation of hemp involves several stages, including soil preparation, planting, management of intermediate processes, harvesting, and fiber separation. Among these, the harvesting of hemp stalks represents the most critical phase. Considering the overall hemp production process, labor and time consumption account for approximately 40% of the total process [18]. Given that the harvesting stage constitutes more than 60% of the total labor requirement in field production, research into harvest mechanization has been emphasized as essential [19]. Therefore, the development of harvesting machinery is crucial in hemp cultivation. Advancements in harvest mechanization will facilitate the production of high-quality fibers.

Although there are similarities among hemp genotypes, differences may arise in cultivation methods and the harvesting process [20]. To provide data for the design of combine harvesters in hemp harvesting, parameters such as cutting speed and stalk feeding rate were analyzed for a prototype combine harvester, and the necessity of these parameters for the design was established [21]. In their studies on hemp stalks, Shen et al. [22] examined cutting force and cutting quality, emphasizing that the results obtained should be utilized in subsequent research.

In addition, the lack of advanced machines suitable for the morphological characteristics of hemp is indicated as the main factor for hemp to be profitable. Therefore, some modifications or device connections are necessary for the existing machines used to harvest hemp stalks [23]. The presence of hard fibers in hemp plant harvesting is also known as a major problem in this regard, as well as the clogging of unsuitable machines [24].

In hemp harvesting, certain harvesting machines have been adapted for use with tractors [25]. However, it is known that some of the machines used in various countries were designed without sufficiently considering the physical characteristics of hemp stalks. This is primarily because the machines currently in use were originally designed and manufactured for harvesting other crops, such as rice and wheat [26]. As a result, these machines cannot

be utilized efficiently or effectively due to the structural characteristics of hemp stalks. Hemp fibers may exhibit diverse mechanical and even electrical properties [27]. Therefore, understanding the physical and mechanical characteristics of hemp is crucial during the development of hemp harvesting machinery. In particular, the design of hemp harvesters takes into account various mechanical parameters, such as tensile tests, compression tests, and bending tests, to ensure optimal performance [28].

During the decortication of hemp stalks, damage often occurs due to compression, leading to deformation that negatively affects the quality of the fibers obtained. Before decortication, the quality of hemp stalks, characterized by factors such as stalk color, mass, diameter, and chemical composition, plays a critical role in determining retting efficiency [29]. Understanding the compression properties of hemp stalks is critically important for designing and improving baling systems or fiber extraction machines used after hemp harvesting [30,31]. The study of the physical and mechanical properties of agricultural products has been a significant focus of research. This is because these properties serve as essential parameters in agricultural machinery design [32].

Studies have reported that compression forces vary based on plant species, stem diameters [33], stem structures, and maturity stages at different plant heights. For instance, in sorghum plants, compression forces were found to differ across various stem heights [34]. Similarly, to obtain fundamental data for combined harvester design, Bhaholyotin et al. [35] investigated sugarcane plants and highlighted that the required force values varied significantly at different stem heights.

In hemp harvesting, it is crucial not only to minimize seed loss but also to reduce mechanical damage [36]. Limited studies have shown that the force and energy values required to cut hemp stalks are higher than those for other plants. Based on these findings, it is expected that the compression properties of hemp stalks will also differ from those of other crops, highlighting the need for further investigation. Additionally, it has been observed that there are differences in volatile emissions between male and female plants [37], emphasizing the importance of minimizing excessive deformation during harvesting.

Male and female hemp flowers differ in their morphological structures, and the plants themselves exhibit distinct characteristics based on sex [38–41]. In hemp cultivation, enhancing male plants' ability to feminize is considered crucial for improving yield [42]. Consequently, understanding the characteristics of plant sex is essential. Given the variation in the length and thickness of hemp stalks, research and design efforts for hemp harvesting machines are essential [19]. Furthermore, in their study on six hemp varieties, Bakali et al. [43] found that gender ratio, plant height, and stem diameter vary according to the different cultivars.

The harvest period plays a crucial role in the chemical profile of flower clusters [44]. In their study on gender determination and plant development in hemp, Barbosa-Xavier et al. [45] identified tissue-specific genes in the plants, providing valuable data for further research. In hemp plants, the efficient extraction of high-quality fibers from the stems without deformation is crucial for industrial applications [46]. Additionally, determining the gender of hemp plants is essential for farmers to improve the crop and enhance its yield [28,47]. Particularly, when examining or utilizing hemp fibers, the gender of the plant must be known and considered [48]. The mechanical properties of fiber hemp stems are a critical factor in optimizing operational parameters [49].

Recent studies highlight that harvesting technologies for obtaining high-quality products, including both seeds and fibers, have not been adequately investigated [50]. Additionally, it seeks to accurately determine the physico-mechanical properties of both male and female plants, ensuring a comprehensive understanding for enhanced harvesting efficiency.

Hemp plants are cultivated as a mixture of male and female plants for both seed and fiber production. Generally, when hemp is grown for fiber, the plants are harvested from the field. The fibers are then separated from the harvested plant stems using specialized harvesting machines. To ensure fiber quality, these machines must be designed according to the mechanical properties of male and female plants. Therefore, determination of design parameters for these specialized machines is necessary.

This study was carried out to provide data for the physical and mechanical properties of male and female hemp plants.

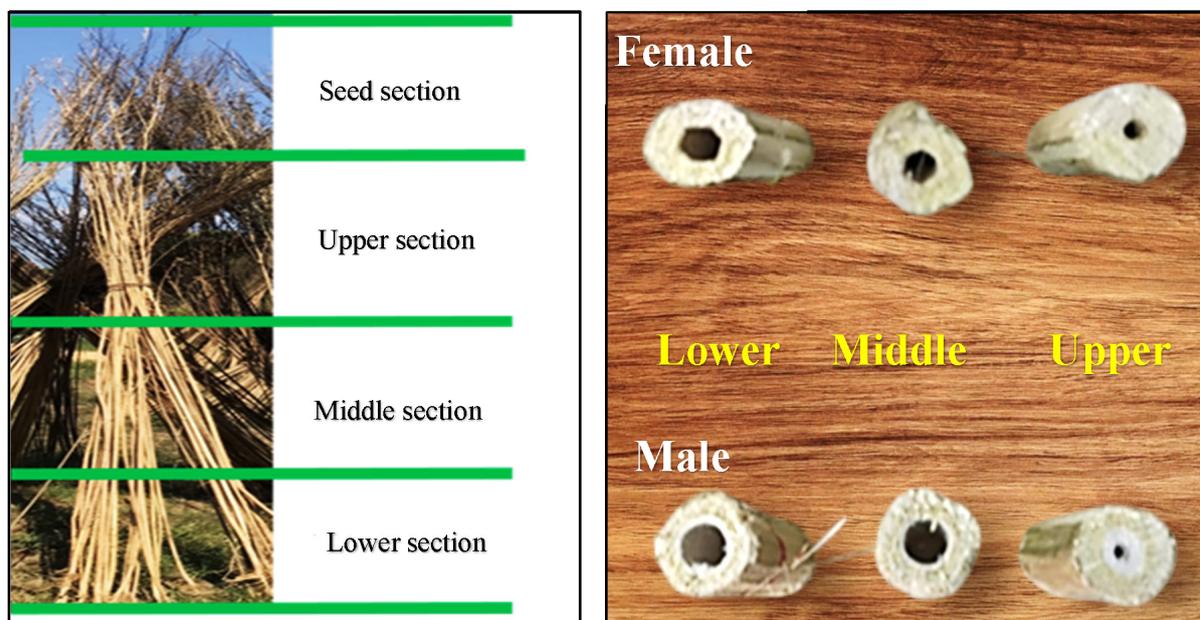
## 2. Materials and Methods

This study was carried out in 2022; the plant samples used in the trials were collected from a hemp field in Narlısaray Village, Vezirköprü District, Samsun Province, Türkiye, where local populations were cultivated for fiber production. In addition, male and female hemp plants were collected separately and labeled.

### 2.1. Determination of Physical Properties

The plant samples collected from the field were separated from their root sections and left to dry naturally. Before testing, the samples were dried to achieve moisture contents of approximately 10%, 10.5%, and 11% for the upper, middle, and lower regions, respectively. These moisture levels were adequate for conducting compression tests on hemp plants.

The dried plant stems were divided into three equal regions (lower, middle, and upper) for further analysis. Mazian et al. [51] similarly divided the plant into three regions—lower, middle, and upper—for sample collection in their study on determining fiber quality in hemp. After dividing the stems into three equal sections, samples measuring 25.4 mm in length were taken from each region as shown in Figure 1.



**Figure 1.** Sampling positions.

The samples extracted from the plant stem were prepared according to the ASTM standard method for compression testing of plastic materials [52]. To avoid any deformation during the cutting process, a precision saw was employed to obtain the samples. Prior to cutting the test samples, the saw was carefully inspected to ensure it did not induce any deformation [53].

### 2.1.1. Measurement and Calculations

The hemp harvest was conducted when the plants reached harvest maturity. In order to determine some of the physical properties of hemp, 20 plant stem samples were randomly collected from both male and female plants.

#### Stalk Diameter

The diameter of each stalk was measured at three positions (lower, middle, and upper) using a digital caliper with an accuracy of 0.01 mm, as described by Abdelhady et al. [54]. All measurements were performed in the laboratory.

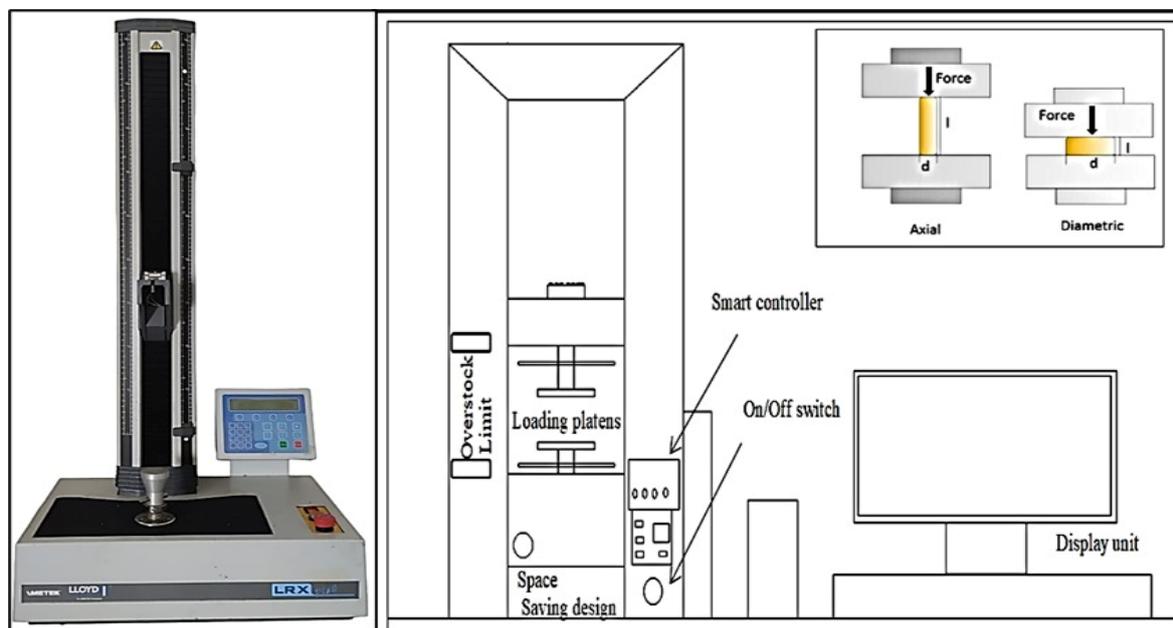
#### Stalk Length

The plant height was measured from the soil surface to the seed-bearing section [55]. After removing the seed-bearing section, the remaining stem was divided into three equal parts.

## 2.2. Mechanical Properties of Hemp Stalk

### 2.2.1. Measurement of the Forces

The mechanical properties (compression forces) of the hemp samples were measured at the Department of Agricultural Machinery and Technologies Engineering, Faculty of Agriculture, Ondokuz Mayıs University, using the “Benchtop Materials Testing Machine”. The testing was conducted using the LD5 Lloyd Instrument testing device (Lloyd Instruments Universal Testing Machines, LRX Plus, Lloyd Instruments Ltd., an AMATEX Company, Meerbusch, Germany), which has a force capacity of 5 kN (1124 lbf) and a crosshead speed range of 0.0001 to 1270 mm/min, as shown in Figure 2.



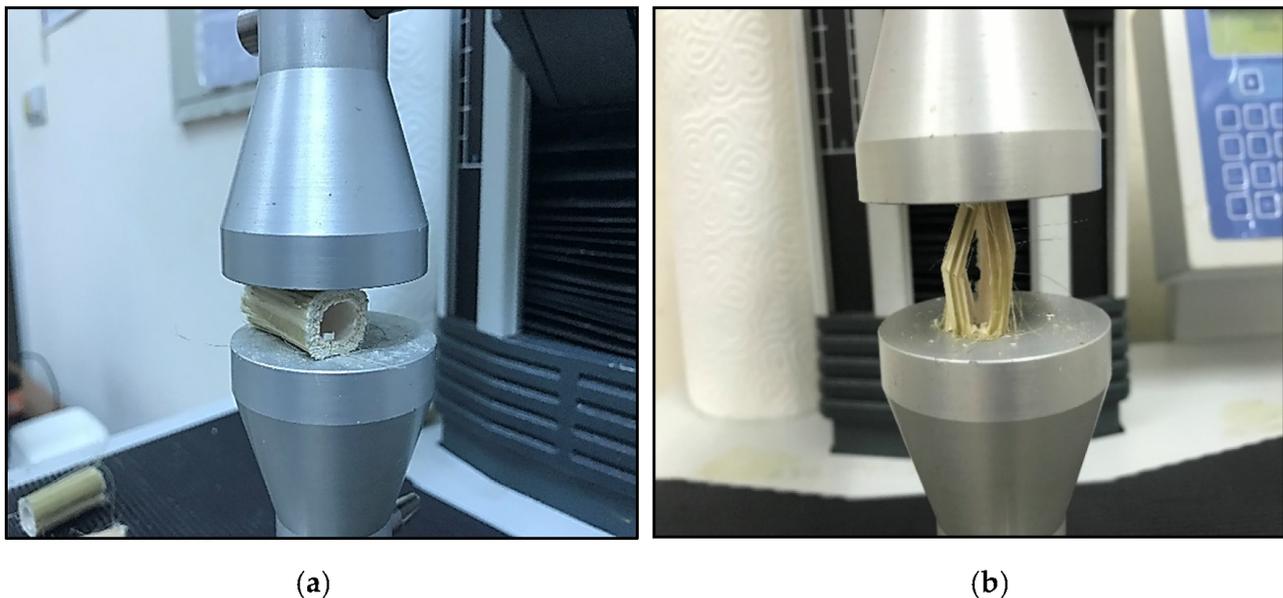
**Figure 2.** A benchtop materials testing device.

Similarly, Aydın and Arslan [56] employed the Lloyd LRX Plus testing device in their study to determine the physical properties of cotton plants. In the bending tests, fiber samples prepared from hemp plates were subjected to testing until broken. The LR5KPlus device, manufactured by Lloyd Instruments, was used for these tests [57,58].

The testing device consists of a main body, a load cell, a compression apparatus, a data acquisition system, and a computer. The device has a capacity of 2500 N, which allows for adjustable loading speeds; a compression rate of approximately 10 mm/min was utilized during the experiments. To enhance the cutting performance of a two-wheeled walking hemp harvester, response surface tests were conducted at three levels for three key factors influencing operational quality: cutting speed, blade length, and forward speed, using a dedicated hemp cutting test bench [59].

### 2.2.2. Measurement of the Stress

Deformations in the hemp plant samples were determined based on the axial and lateral forces applied to them. Prior to the compression test, the samples were positioned in the testing device both axially and laterally, as illustrated in Figure 3. Using the testing device, a force was then applied to the samples at an average speed of 10 mm/min.



**Figure 3.** Compression stress determination: lateral (a) and axial (b) force application using the testing device.

### 2.3. Compression Experiment Design

The experiments were conducted by separating male and female hemp samples. The hemp plant samples were examined based on two different types (male and female), three distinct height regions (lower, middle, and upper) [60], and two different compression directions (lateral and axial) [31]. In this study, each experiment was carried out with 30 replications. Following the method outlined by Zhou et al. [28], measurements of the inner diameter (mm), outer diameter (mm), and thickness (mm) were recorded for each sample extracted from the plant stems.

### 2.4. Statistical Analysis

The study was carried out using a factorial experimental design with randomized plots, incorporating a total of 30 replicates. The physical and mechanical properties of the samples were analyzed through analysis of variance (ANOVA) to assess the effects of different treatments. To further determine the statistical significance of the observed differences, the least significant difference (LSD) test was applied, with a significance level of  $p < 0.05$ . The statistical analysis of the experimental data was carried out using the SPSS (version 15, SPSS Inc., New York, NY, USA) software, a microcom-

puter program, which was used to statistically examine the values of the physical and mechanical properties.

### 3. Results

#### 3.1. Physical Properties of Hemp Stalks

The measurements conducted on samples taken from the stem of the hemp plant are presented in Table 1. When comparing male and female hemp plant samples, it is evident that male hemp exhibits larger values than female hemp in terms of inner diameter, outer diameter, and thickness. When the variations in plant samples are evaluated in terms of the direction of the applied force, it can be stated that the thickness values in the axial direction are slightly higher than those in the lateral direction, with measurements of 2.562 mm and 2.413 mm, respectively. However, no significant difference is observed in terms of inner and outer diameters.

**Table 1.** Physical measurements of the hemp plant.

Sources of Variation	Parameters		
	Thickness (mm)	Inner Diameter (mm)	Outer Diameter (mm)
Sex			
Male	2.628 ± 0.71 a	4.452 ± 1.26 a	9.708 ± 2.20 a
Female	2.347 ± 0.71 b	3.986 ± 1.36 b	8.681 ± 2.23 b
Direction			
Axial	2.562 ± 0.67 a	4.162	9.286
Lateral	2.413 ± 0.76 b	4.277	9.104
Section			
Lower	3.149 ± 0.67 a	4.915 ± 1.05 a	11.142 ± 1.71 a
Middle	2.335 ± 0.50 b	4.843 ± 0.95 a	9.585 ± 1.27 b
Upper	1.978 ± 0.39 c	2.901 ± 0.83 b	6.857 ± 1.24 c
LSD			
Sex	0.0334 *	0.0648 *	0.0829 *
Direction	0.0334 *	n.s	n.s
Section	0.0409 *	0.0794 *	0.1016 *
CV (%)	0.1779	0.2035	0.1195

n.s: not significant; \*:  $p (\leq 0.05)$ : The letters indicate statistically different groups.

When the samples taken from the hemp plant are analyzed by region, it is observed that the thickness, inner diameter, and outer diameter decrease from the lower to the upper sections of the stem. Additionally, it was determined that the moisture content of the compression test samples decreased from the lower to the upper section of the stem.

#### 3.2. Mechanical Properties of Hemp Stalks

##### 3.2.1. Determination of the Forces

The variations in male and female hemp plant samples based on the applied load values were analyzed according to sampling regions (Table 2). The applied load values were determined to be 877.396 N and 670.390 N for male and female samples, respectively. When considering the load values applied to hemp samples in the axial and lateral directions, it was observed that the load applied in the axial direction was higher, reaching 1436.091 N.

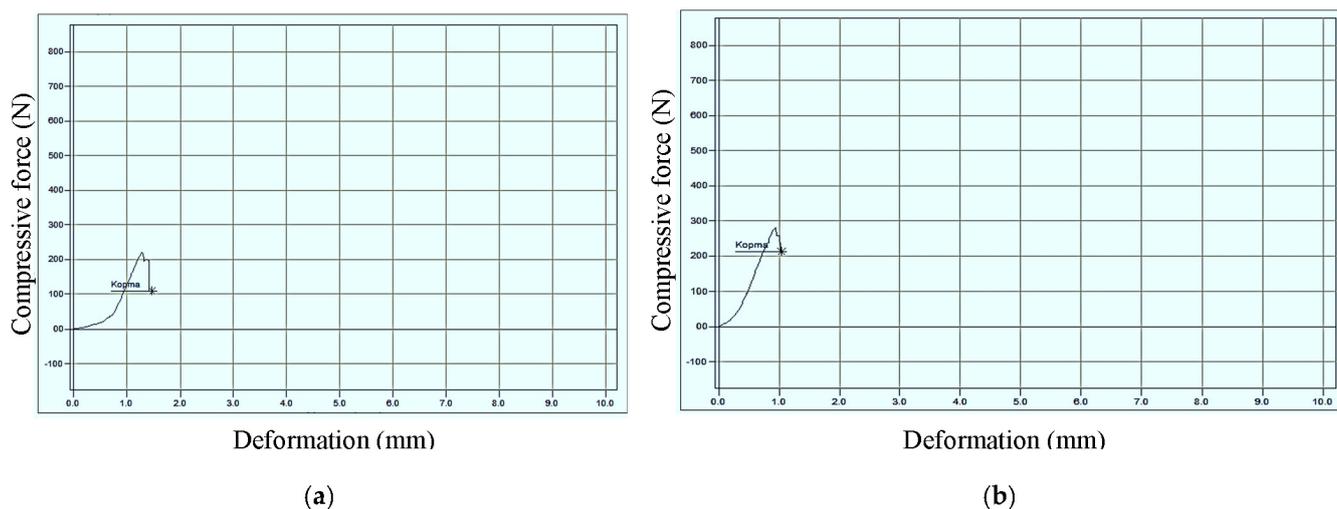
**Table 2.** Load, deformation, and energy characteristics of hemp samples.

Sources of Variation	Parameters		
	Load (N)	Distance (mm)	Energy (J)
Sex			
Male	877.396 a	1.888 a	1.403 a
Female	670.390 b	1.781 b	1.068 b
Direction			
Axial	1436.091 a	2.949 a	2.423 a
Lateral	111.695 b	0.719 b	0.048 b
Section			
Lower	1025.566 a	2.024 a	1.634 a
Middle	765.345 b	1.853 a	1.261 b
Upper	530.768 c	1.627 b	0.812 c
Sex × Direction			
Male–Axial	1627.584 a	3.091 a	2.762 a
Female–Axial	1244.598 b	2.808 b	2.085 b
Male–Lateral	127.208 c	0.685 c	0.044 c
Female–Lateral	96.182 c	0.754 c	0.052 c
Direction × Section			
Axial–Lower	1911.262 a	3.119	3.190 a
Axial–Middle	1434.081 b	3.010	2.482 b
Axial–Upper	962.932 c	2.718	1.597 c
Lateral–Lower	139.870 d	0.930	0.078 c
Lateral–Middle	98.605 d	0.695	0.039 c
Lateral–Upper	96.611 d	0.536	0.027 c
LSD			
Sex	21.9215 *	0.0270 *	0.0444 *
Direction	21.9215 *	0.0270 *	0.0444 *
Section	26.8482 *	0.0331 *	0.0543 *
Sex-Direction	31.0016 *	0.0382 *	0.0627 *
Direction–Section	37.9691 *	n.s	0.0769 *
CV (%)	0.3754	0.1951	0.4759

n.s: not significant; \*:  $p (\leq 0.05)$ : The letters indicate statistically different groups.

When examining the male and female hemp samples in terms of the direction of the applied load, it was found that the axial force values were higher than the lateral force values for both male and female samples (Figure 4). In male hemp samples, the highest load value was recorded in the axial direction at 1627.584 N, while the lowest load value was observed in female hemp samples under lateral load application, measuring 96.182 N.

These data indicate that male hemp samples are subjected to greater deformation under higher loads in both axial and lateral directions. Considering the sections along the hemp plant from which the samples were taken, it was observed that the load values decreased from the lower to the upper section for all samples in both axial and lateral directions. Overall, the load values in the axial direction were higher than those in the lateral direction. The highest load value, 1911.262 N, was recorded in the axial lower section, while the lowest load value, 96.611 N, was observed in the lateral upper section.



**Figure 4.** Fracture values of samples under axial (a) and lateral (b) force applications.

### 3.2.2. The Compression Stress

Table 2 indicates that the elongation values of male and female hemp samples were found to be 1.888 mm and 1.781 mm, respectively, which are relatively close to each other. Although the elongation amounts in male and female hemp samples appear similar, they belong to statistically different groups. In the samples, the elongation in the axial direction was 2.949 mm, while in the lateral direction, it was 0.719 mm. The smaller elongation in the lateral direction indicates that the plant underwent deformation without experiencing significant elongation. When examining the elongation values based on the regions from which the samples were taken, it was observed that the elongation decreased from the lower to the upper section. The elongation was 2.024 mm in the lower section, while it was 1.627 mm in the upper section. Considering that the stem is thicker in the lower section and becomes thinner towards the upper section, this pattern can be regarded as a natural outcome. When examining the elongation of male and female plant samples in different directions, it was found that the elongation values in the axial direction were higher than those in the lateral direction for both male and female samples. In male plant samples, the maximum elongation was observed in the axial direction, measuring 3.091 mm, while the minimum elongation was recorded in the lateral direction in female samples, at 0.754 mm.

The highest energy consumption in hemp plants was observed in male samples at 1.403 J and in female samples at 1.608 J. Regarding compression direction, the highest values were required in the axial direction. Specifically, deformations occurred with energy values of 2.423 J in the axial direction and 0.048 J in the lateral direction.

When the energy values of the hemp plant were analyzed according to different regions, it was found that the values decreased from the lower to the upper region of the plant. Furthermore, there was an approximately 2 times difference in energy values between the lower and upper regions, highlighting a significant variation along the plant's vertical axis. On the other hand, when the energy requirements of male and female plant samples were analyzed based on compression direction, it was observed that higher energy was consumed in the axial compression for both male and female samples. Specifically, the axial compression required 2.762 J for male samples and 2.085 J for female samples. In contrast, the lateral energy values were significantly lower, measured at 0.044 J for male samples and 0.052 J for female samples. These findings emphasize the directional variation in energy consumption between the axial and lateral compressions.

When the compression direction and regions of the hemp plant were evaluated together, the energy values in the axial direction were found to be significantly higher than

those in the lateral direction. Additionally, the required energy values in both axial and lateral directions decreased from the lower to the upper regions of the plant. The highest energy value was recorded at 3.190 J in the axial direction of the lower region, while the lowest energy value was 0.027 J in the lateral direction of the upper region.

#### 4. Discussion

The compression forces applied to the samples obtained from the plant were used to measure load, elongation, and energy values. It was determined that the thickness, inner diameter, and outer diameter values differed between male and female samples, with higher values observed in male samples. Moreover, all three parameters decreased from the lower to the upper section of the plant stem. This variation in stem diameters suggests that the force required for fiber separation from the stems will also vary accordingly. Li et al. [61] found that the fiber dimensions in different sections of the hemp stem varied significantly. In their study, the hemp stem was divided into five distinct regions, and samples from each region were thoroughly analyzed. Similarly, İnce et al. [62] investigated the bending stress, modulus of elasticity, shear stress, and specific cutting energy for sunflower (*Helianthus annuus* L.) stems. Their research divided the sunflower stem into four regions and demonstrated that cutting energy values varied significantly across different stem sections.

It can be stated that the required load values increase from the lower to the upper section of the plant stem. This can be explained by the increase in stem thickness from the lower to the upper section. Similarly, in their study on the compressive strength of bamboo, Lo et al. [63] observed that the compressive strength decreased with the height of the stem. It was found that male hemp samples underwent more deformation under higher loads compared to female samples. This indicates that male hemp samples have a stronger structure. Hemmatian et al. [58] conducted a study to determine the mechanical properties of sugarcane stalks by collecting samples from ten different heights along the plant stem. Their findings revealed that cutting speed and stalk height significantly influenced both cutting force and cutting energy.

The results aligned with the mechanical test results, indicating that the failure mechanism significantly depends on the quality of specimen preparation. Similarly, Mazian et al. [51] examined samples taken from the lower, middle, and upper sections of the hemp plant, concluding that the position of the samples significantly influences fiber quality. In their study on corn plants, Chen et al. [64] divided the stalk into four sections to determine the cutting forces required at different harvest dates. They observed that cutting force decreased from the lower to the upper section of the stalk. The results of their study were analyzed using the SPSS statistical program.

In hemp, the energy values in the axial direction were higher than those in the lateral direction across both the direction of load application and the regions where the force was applied. This indicates that, for both directions, the energy values decreased from the lower to the upper section. Similarly, Boydaş et al. [65] divided the alfalfa stem into three regions to determine properties such as cutting stress and specific cutting energy. They found that both cutting stress and specific energy values decreased towards the upper regions of the stem. The largest outer diameter value (11.142 mm) was found in the lower section, while the smallest thickness value (1.978 mm) was recorded in the upper section (Table 1). Similarly, Chen et al. [66] reported that the characteristics of hemp stalks vary within the field and that the mechanical properties, including the cutting energy requirement, depend on the stem diameter. Similarly, in barley, shear strength and shear energy varied according to moisture content and stem diameter [67]. Moreover, it was evaluated through variance analysis that, in addition to moisture content, the stem level also influenced the results, as

determined by Duncan's multiple range test [68]. Similar results were found by O'Dogherty et al. [69] for wheat straw and by Halyk [70] for alfalfa stems.

Similarly, in the case of hemp, it is necessary to develop methods for mechanical harvesting with minimal energy consumption [28]. The data obtained from compression tests are essential for understanding the compressive strength of hemp stems, which is a crucial factor in the design of hemp processing machinery. The compressive strength of hemp stems is crucial for the design of hemp processing machinery [31].

## 5. Conclusions

In this study, the male samples exhibited higher values in thickness, inner diameter, and outer diameter compared to the female samples. Specifically, the thickness, inner diameter, and outer diameter of male hemp were 2.628 mm, 4.452 mm, and 9.708 mm, respectively, while these values for female hemp were 2.347 mm, 3.986 mm, and 8.861 mm.

Generally, male hemp samples exhibited greater increases in thickness, inner diameter, and outer diameter from the lower to the upper regions compared to female samples, reflecting distinct structural differences.

In male hemp, the values of load, elongation, and energy were higher compared to female hemp. It was observed that axial compression loads were greater than lateral compression loads. Specifically, the load values were 1436.091 N in the axial direction and 111.695 N in the lateral direction. In male hemp, both axial and lateral compression loads were higher than those in female hemp, with values ranging from 1627.584 N to 96.182 N. Furthermore, in hemp, axial compression loads decreased from the lower to the upper regions of the plant. A similar trend was observed in lateral compression, indicating a consistent pattern of load distribution across the plant's structure. When examining the elongation and energy requirements in both axial and lateral compressions, a similar pattern was observed with the load values.

In particular, when mixed planting of male and female hemp is practiced, it is important to consider the characteristics of male hemp. This highlights the significance of incorporating gender-specific characteristics in the design process to optimize harvesting efficiency. Based on the results obtained from this study, it is evident that understanding the physico-mechanical properties of male and female hemp is crucial for the design of hemp fiber separation machines.

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