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An Analysis of Structural Integrity and Durability in Determining the Optimal Compaction Parameters for Hemp and Pine

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Abstract: Research on seed hemp and pine was carried out to improve sustainability and energy efficiency. The mechanical properties of different species of lignocellulosic biomass are still undocumented in the context of granulation processes, even though lignocellulosic biomass is widely studied for biofuel production. Hemp and pine have not been thoroughly compared in the granulation process. Under compressive forces pertinent to pelletizing, the study investigated the mechanical properties of lignocellulosic materials, such as hemp and Scots pine. Based on their mechanical properties, microscopic analysis and strength tests were conducted to compare hemp pellets and pine briquettes. In recent years, a significant trend has been towards eco-friendly and innovative biofuel production, motivating research on compaction technologies and material strength enhancement. The study compared hemp (*Cannabis sativa* L.) with Scots pine (*Pinus sylvestris*) during compaction. Compared with pine briquettes, hemp pellets exhibit superior mechanical durability (durability factor = 0.98) and compressive strength (average 2.5 kN), demonstrating hemp's potential as a renewable fuel source. The study results contribute to the development of sustainable biofuel production processes.

Keywords: bioenergy; hemp stalk; pine residues; pellets and briquets

Academic Editor: Byong-Hun Jeon

Received: 20 January 2025
Revised: 18 March 2025
Accepted: 24 March 2025
Published: 7 April 2025

Citation: Roman, K.; Wardal, W.J.; Maksymiuk, G. An Analysis of Structural Integrity and Durability in Determining the Optimal Compaction Parameters for Hemp and Pine. *Energies* **2025**, *18*, 1853. https://doi.org/10.3390/en18071853

1. Introduction

Despite increasing research on lignocellulosic biofuels, the benefits of biomass as a sustainable energy source are well-established. Compaction processes of various biomass types remain poorly understood, especially regarding mechanical properties. Pretreatment, densification, and combustion characteristics have been explored in previous studies, but the relationship between mechanical properties and overall performance, including production, handling, and storage, has been underexplored. This study aims to fill this gap by analyzing hemp and pine biomass's mechanical properties and durability during compaction. As a result of these findings, biofuel applications can be examined, and the relationship between compaction parameters, structural integrity, and durability can be better understood, ultimately enabling the development of more efficient and sustainable bioenergy technologies [1,2]. An effect of the conducted energy policy was adapted to the European Union's energy and climate package objectives. The heating and power industry has improved its environmental solutions over the past few years.

Using strategy led to greater interest in managing and using publicly available, eco-friendly waste materials worldwide. Hemp, wood chips, and forestry waste also belong to the group, along with lignocellulosic biomass such as hemp [3]. Biomass is increasingly used for heating and energy production from agricultural and forestry residues. Coal, oil, and natural gas combustion emits substantial greenhouse gases and dust. Reducing pollution requires the use of renewable energy rather than fossil fuels. There is an increase in the use of renewable energy technologies in Poland and throughout the world. Sustainability is enhanced by the use of biomass in the energy industry. The biofuel potential of hemp and Scots pine is high due to their high levels of lignocellulosic biomass. Comparisons of their compaction behavior, mechanical strength, and energy efficiency are limited. The present study evaluated hemp and pine under compression forces to determine their structural integrity and biofuel potential.

There has been a growing interest in hemp due to its potential for producing organic and sustainable products [4]. The potential benefits of hemp as a sustainable, ecological resource have rekindled interest in hemp in recent years [5,6]. The growing demand for sustainable materials has led to increased research on hemp fiber processing and modification techniques to enhance its properties and expand its applications. Sustainable development can be achieved using plant materials, which has many benefits. The application of hemp can be found in both traditional and innovative fields. Innovations in the hemp processing industry can also affect the development of new products. The plant has gained popularity because of its diverse applications. Hemp structures exhibit notable strength and durability, attributed to the presence of lignin in the cell wall, making them suitable for various applications) [7–9]. The hemp cell wall is filled with lignin, an organic polymer complex that provides strength and durability [7,8]. Lignin is an essential component of lignocellulosic materials that impacts their performance significantly [9,10]. This is necessary to ensure the durability of the resulting products when transporting biofuel.

Forest residues, including branches, bark, needles, and small-diameter wood, represent a significant source of untapped renewable energy in Poland, with an estimated potential of 4.9 million m^3 annually [11]. Utilizing these residues for bioenergy production can contribute to a sustainable energy future by reducing reliance on fossil fuels and greenhouse gas emissions. Bioenergy production from forest residues can also stimulate rural economies by creating jobs and income opportunities and promoting forest health by mitigating fire hazards and disease outbreaks. The proper management of forest residues is crucial. Undeveloped wood, especially wood that contains a high proportion of rot, can disturb the forest ecosystem by promoting microbial disorders [11]. The material can also be restricted in its ability to be used for energy and hinder silvicultural treatments. Forest management practices that emphasize sustainable management are necessary to prevent fires caused by dry logging residues. To meet these challenges and maximize the potential of forest residues, several approaches can be employed:

- The method prepares residues for use as energy or biological management, such as composting;
- Chopping the biomass on-site and mixing it with the soil releases valuable nutrients, fertilizing the area once logging has been completed;
- The material is densified by compaction into briquettes or pellets, making it easier to handle, transport, and burn.

The potential of hemp (*Cannabis sativa* L.) and Scots pine (*Pinus silvestris*) lignocellulosic biomass for sustainable biofuel production is being investigated. Optimal parameters for biofuel production will be determined by examining these biomass types' mechanical properties and durability during compaction. During compaction, the mechanical properties of hemp and pine are compared, the optimal compaction parameters are identified for maximizing the durability and structural integrity of each biomass type, and the microstructure of biofuels are studied as a result of compaction. Based on these findings, biofuel production technologies can be developed more efficiently and sustainably. The study investigates biomass mechanical properties and durability to determine biofuel productions' ideal sustainable compaction parameters. It examines these materials' structural integrity, durability, and suitability for biofuel applications under various compaction conditions. Although lignocellulosic materials have played a significant role for centuries in industries such as wood and furniture, their residues can also generate renewable energy. The research focuses on the compaction process, studying the mechanical properties of both hemp and pine under briquetting pressures.

2. Materials and Methods

2.1. Materials

2.1.1. Hemp (*Cannabis sativa* L.)

Several key components influence the chemical composition of hemp. A significant component that makes it both strong and elastic is cellulose, one of its key components [1,2]. Cellulose, hemicellulose, and lignin comprise most of the fiber's exterior and are the main elements of its cell wall. The average natural contents of the product range from 70 to 80%. Lignocellulosic biomass also contains hemicellulose, a polysaccharide composed of many sugar units. It supports cell walls, and its properties, such as flexibility and water retention, are influenced by it. The hemicellulose content in a plant can vary depending on its species and growth environment. The biomass structure can maintain its strength, elasticity, and structural integrity because of cellulose, while lignin helps retain its structural integrity. The wood structure of hemp can be divided into fibers and shaves. The natural fiber of hemp is available in many shades of brown, gray, and green, which, along with its distinctive appearance, enhances its natural appeal. It also comes in several shades of black. Hemp fibers are solid due to the specific arrangement of microscopic threads of cellulose, called microfibrils, which run along the fiber's axis and interact with other cell wall components to provide exceptional strength and durability. In hemp shaves, the water channels within plant cells contribute to the balance of moisture, resulting in crystal and crystal clusters, affecting the cell's structure. Hemp shives, containing organic substances like pectin, exhibit versatility and can be utilized in various applications due to their inherent strength and structural integrity. Among the physical properties of hemp are adhesion and moisture resistance, which are affected by pectin and wax. The chemical composition of hemp makes it an attractive raw material for many industries [12–15].

2.1.2. Pine (*Pinus silvestris*)

Pine wood is indispensable from a global perspective, mainly due to its wide range of uses in the construction, furniture, and paper industries, as well as its high availability and economic value. Pine is a valuable wood resource and raw material many countries use worldwide. The species commands a high price on the global market due to its favorable properties and attractive appearance. Pine wood is one of the world's most important types of wood, as it is in high demand. The study material was collected from a forest plot in a dry forest environment. Ponderosa pine (*Pinus silvestris*), aged 70–80 years, appears to dominate the study area. Selecting species that grow in temperate climates and suitable soil substrates was important. There was a wide variation in the size and structure of individual elements in the material before processing. A problematic aspect of the wood was its anisotropic nature, which presents challenges when determining its homogeneous strength. For further research, sapwood and heartwood were obtained to choose the most appropriate wood. The suggestion to obtain the material was based on industry practice, focusing on wood characteristics such as sapwood and heartwood. In the study, the heartwood of the trees was used since the part of the wood is often used in solid timber structures.

2.2. Optical Microscope Image Analysis

The optical analysis of lignocellulosic materials under a microscope involves key steps to examine their structure. The sample was sectioned and analyzed using a Nikon SMZ 1500 microscope (Melville, NY, USA) with an external light source. A digital camera captured images, which were enhanced using filters to improve contrast. The stereoscopic microscope, with a zoom range of 0.75–112.5, provided both macro and micro views. A 150-Watt halogen illuminator ensured proper lighting, while an optical system corrected chromatic aberrations. Structural characteristics were evaluated by comparing images, aiding in material identification and classification. Appropriate interpretation and documentation of results ensure a thorough understanding of the material.

2.3. Strength Analysis

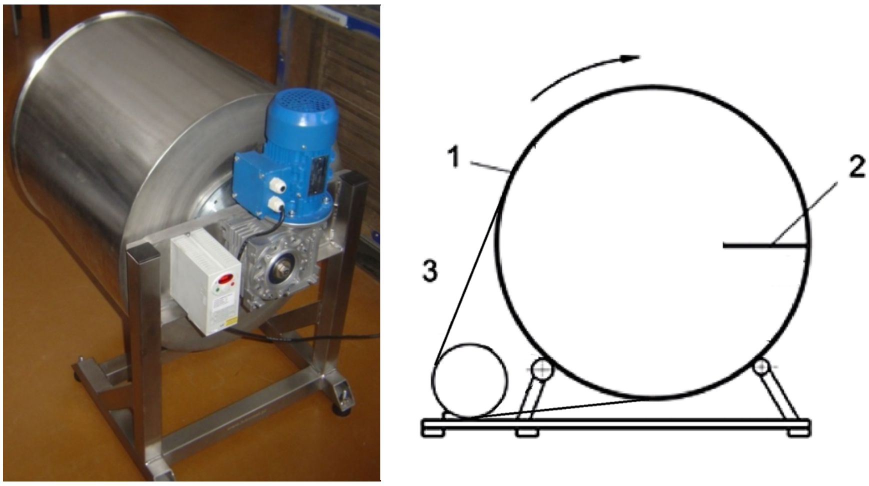
Before processing, uniaxial compression tests were performed on raw samples, following the ASTM ISO standard [16] to evaluate material strength. The study included five hemp samples (ø20 × 30 mm) and four Scots pine samples (20 × 20 × 30 mm), with these dimensions representing the samples before compaction. Due to differences in their natural structure and processing techniques, the two materials exhibited distinct geometries—hemp samples were cylindrical, while Scots pine samples were rectangular. To ensure accurate and meaningful comparisons, the compressive force was normalized using the cross-sectional area of each sample. This approach allowed for a direct assessment of the mechanical performance of both materials, accounting for their differing shapes and structural characteristics [16,17].

An Instron universal testing machine performed tests at 20 °C and 50% relative humidity. The machine recorded the maximum destructive force, divided by the cross-section, to determine compressive strength in MPa. The stress–strain relationship was analyzed to evaluate structural behavior under load. The results were influenced by wood anisotropy, moisture content, defects, and resin presence. Latewood density played a key role in strength variations. The testing machine ensured precise, repeatable measurements, generating stress–strain diagrams that provided insights into material stiffness and compressive resistance.

2.4. The Technical Measure (Moisture and Durability)

To maintain proper moisture levels, pellets, briquettes, and mechanical test samples were prepared from raw material dried at 105 °C. As recommended in the literature, moisture content was measured using a calibrated laboratory cuvette, ensuring 12% moisture retention. Since pelletizing and briquetting require different moisture levels, environmental factors like temperature and humidity were considered. Moisture content was verified before each test using a Radwag MAC 50 scale (Radom, Poland).

Briquette durability was tested according to ASTM ISO standard [17]. Samples (2 kg ± 100 g) were placed in a rotating drum for 120 s to measure weight loss and resistance to storage and transport. The residual material was sieved through a 35 mm mesh. The durability coefficient (Ψ) was calculated based on the remaining mass after testing, providing a quality assessment of the briquettes and pellets. The set for durability measurement and the schematic of its construction are presented in Figure 1.



(a) (b)

Figure 1. The set for durability measure: (**a**) set: device; (**b**) 1—drum, 2—baffle, 3—drive unit 2.5.

The grain size of the material used for strength analysis was determined following the durability test, which measures mechanical resistance. To evaluate the resistance of compacted products (briquettes and pellets) to fragmentation and abrasion during storage and transportation, the products were placed inside a rotating drum subject to controlled mechanical stress. Standard test procedures require the material to be sifted through a sieve in which the mesh diameter is 2/3 the diameter of a single compacted product, allowing the measurement of the fraction of material disintegrated. The durability coefficient (Ψ) is the ratio of mass retained on the sieve to the total initial mass of the sample, serving as an indicator of mechanical integrity and cohesion. In the disintegrated fractions, the maximum grain size did not exceed 8 mm, which was determined by the size of the sieve openings and the shredding process conducted before densification. In order to ensure that the fractions obtained matched the densification chamber's requirements, a shredder was used to prepare the material. This avoided the possibility of oversized particles interfering with the densification process.

2.5. Determination of Residual Mineral Content

The study involved proximate chemical analysis (moisture content, volatiles, solid carbon, and mineral residues after combustion) and ultimate chemical analysis (C, H, O, N, S) (elemental composition of C, H, O, N, S). Analysis was carried out to better understand the properties and potential of the studied raw materials. According to the reviewer's recommendation, residual mineral content after combustion was replaced with residual mineral content after combustion. Ashes are only formed once biomass is burned in its raw state. It does not contain any. To ensure consistency with the scientific literature and testing standards, the analysis was carried out according to ASTM ISO standard [18], which is a standard for determining mineral content in solid biofuels.

The chemical composition of the samples was evaluated by determining residual mineral content after combustion through controlled incineration. To ensure accuracy, tests followed a standardized procedure. The samples (~2 g) were pre-dried and then incinerated at 805 °C in a muffle furnace for two hours. The crucibles were cooled in a desiccator to prevent moisture absorption, and the remaining ash was weighed. Residual mineral content after combustion, calculated as a percentage of the original sample weight, provided insights into mineral composition. A uniform incineration process ensured reproducibility. The analysis helped assess the suitability of materials like hemp and pine for biofuel production. The behavior of biomass in thermal processes such as gasification or combustion in boilers can be evaluated after combustion. Results show the elemental composition (C, H, O, N, S) of the studied raw materials after combustion.

The study primarily evaluates the physicochemical properties of hemp and pine biomass as energy sources. Despite the fact that mechanical properties of combustion residues, such as hardness and compression strength, can affect the design of high-temperature industrial systems, these properties are not critical when selecting biomass fuels for densification and small-scale thermal applications. Process methods also affect particle size distribution, binder composition, and densification pressure, influencing mechanical behavior. The study's objective is to characterize raw materials rather than processed biofuels (e.g., pellets or briquettes), so additional mechanical tests are not necessary to determine their energy potential.

2.6. Statistical Analysis

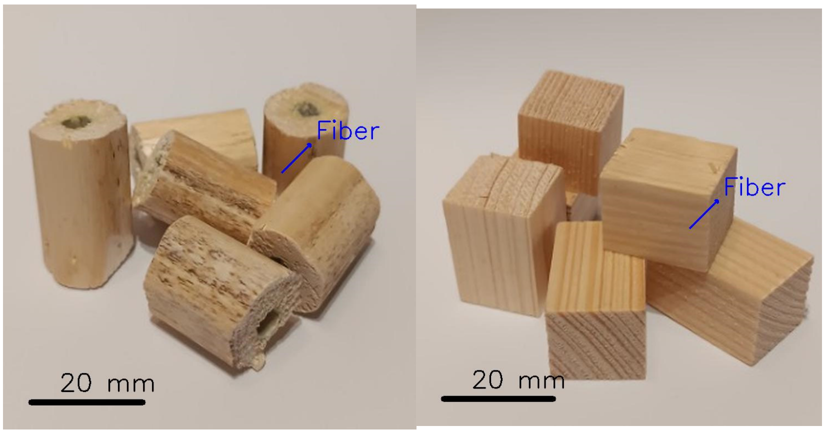
The variances of the groups were compared using ANOVA, and significant differences were tested. A key aspect of the process was formulating null hypotheses (H0: no significant differences) and alternative hypotheses (H1: significant differences) and collecting relevant data. In ANOVA, regular data distribution and equal variances of groups are assumed, and both assumptions have been proven true. When p-value > 0.05, H0 is rejected, indicating a significant difference [16]. Duncan's post-hoc test was used after significant ANOVA results to determine homogeneity within a group. Hypotheses were formulated, data were collected, assumptions were verified, and statistical analysis was conducted [17,18]. The type of ANOVA (univariate or multivariate) depends on the number of factors that influence the dependent variable.

3. Results

3.1. Hemp and Pine Material Characteristic

The study material was obtained from logging operations in Mazovia Forest District as logs. The material for the survey was collected from a forest plot in a dry coniferous forest. The study area appears to be dominated by Scots pine (*Pinus silvestris*). Climate and soil substrates were suitable for the selected species. The study used the Scots pine, a species with a long history of use that is becoming more important as a sustainable and ecological resource. Temperate climates are ideal for the growth of the common pine. The material had a wide range of size and structure before treatment. The average pine tree contains 58.30% cellulose, 11.41% pentosans, 28.45% lignin, and 4.95% extractives. Scots pine, also known as common pine, is the most commonly planted and harvested tree species in Polish forests [19]. Although the hemp and pine biomass compositions were determined by proximate analysis, ultimate analysis, which provides in-depth elemental breakdowns (carbon, hydrogen, nitrogen, sulfur, oxygen), was not performed.

A study was conducted on five independent samples of hemp (n = 5) and four independent samples of Scots pine (n = 4) to determine the compressive strength of the samples. The replication was aimed at balancing material availability constraints with the need to generate reliable data. Variance analysis is used to evaluate the consistency and variability within the data to enhance statistical rigor. The relatively small sample size may limit the robustness of these analyses. To ensure the reliability of mechanical property measurements, conditions during testing were carefully controlled to minimize external variability. The shape of hemp and pine materials is presented in Figure 2.



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

Figure 2. Material: (**a**) hemp, (**b**) Scots pine.

The hemp raw materials were supplied by the company Cannabotanique. The hemp plantation was located in the Mazowieckie Voivodeship in Poland. To determine the potential of hemp (*Cannabis sativa* L.) for material production, it is crucial to analyze its tensile and compressive strength, mainly focusing on hemp fibers and shives. As a lignocellulosic material, hemp is similarly promising due to its high tensile strength and the possibility of using hemp shives instead of pine wood for hardboard production. The tensile strength of hemp fibers, which are used for making rope, as well as the compressive strength, which is relevant to hemp shives as alternatives to pine wood (*Pinus sylvestris*) for shive boards, were examined to realize the potential of the raw material fully.

The forestry potential is also expressed in its production functions. The resource provides raw timber, which is highly valued. The content of individual wood components in harvested material can be of interest from the perspective of harvesting potential. The timber industry can manage individual elements of pine based on the analysis of the structure of the content of each part of wood [20,21]. Pine wood is becoming increasingly efficient as technology allows it to be processed into innovative products like biocomposites or biofuels. Pine cultivation and processing create jobs and benefit local communities, making it a valuable natural resource with numerous benefits. Both pine and hemp produce mechanical properties that can be analyzed to understand their potential better and optimize production processes, enabling more sustainable and eco-friendly solutions to be implemented.

3.2. Material Moisture Content

Moisture content plays an important role in biomass utilization, influencing combustion efficiency, energy output, storage stability, and densification. Higher moisture levels require additional drying, increasing energy consumption and emissions, and the possibility of microbial degradation during storage while reducing overall combustion efficiency. To ensure stable performance in thermal conversion systems, hemp biomass may require pre-drying due to its greater moisture variability. Alternatively, pine maintains a more stable moisture content, which makes it a more reliable feedstock with predictable combustion behavior. The findings underscore the importance of moisture control in biomass processing and energy conversion efficiency, ensuring sustainable and practical application of renewable energy. The moisture content of the tested hemp and pine samples was determined, and the results are summarized in Table 1.

Table 1. The moisture content of the tested hemp and pine samples.

Material	Total Work Involved in Stretching (SD), J
Hemp	12.25 (0.42) [a]
Pine	12.02 (0.18) [a]

[a]—homogenous group; SD—standard deviation.

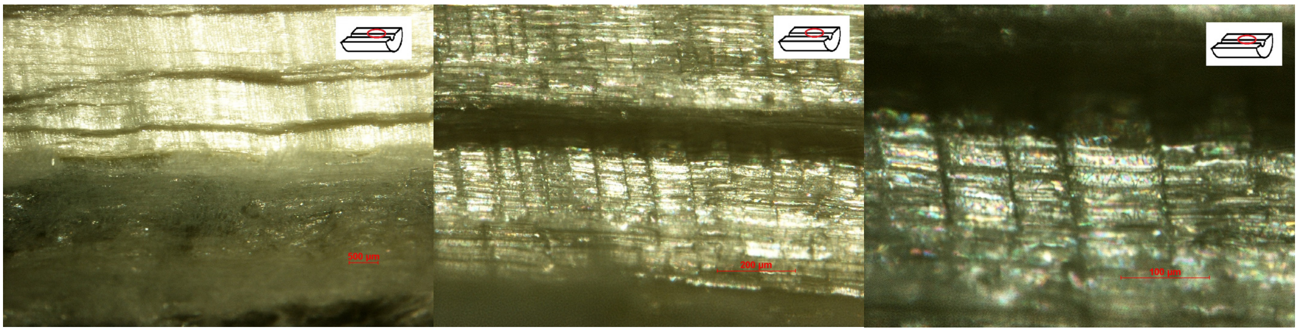
The moisture content of freshly harvested lignocellulosic materials is about 53%, which can negatively impact their storage, handling, and suitability for energy generation. A lower moisture content is typically required for biomass densification to prevent microbial degradation while ensuring enough moisture for effective compaction, efficient processing, and improving fuel stability. According to the higher standard deviation, hemp sample moisture content (12.25%) was slightly higher than pine sample moisture (12.02%) in this study. As a result of their differing structural properties, these biomass materials have different moisture retention properties, such as hemp, due to their fibrous nature and ability to store and release water. The moisture content observed reflects storage conditions used for densification to maintain optimal pelletization and briquetting parameters while minimizing the energy costs associated with drying. It considers both chemical and physical properties of the tested materials to optimize their use in biofuel systems and industrial applications by integrating moisture content analysis.

3.3. Optical Microscope Image Analysis of Hemp and Pine Shaves

The study also analyzed the lignocellulosic materials and the cellular structure of hemp and pine stems using optical microscopy. The technique allows for observing morphological and structural characteristics, such as fiber arrangement, cell size, shape, and potential flaws [22]. To further process lignocellulosic materials, it is essential to understand the relationship between the structure and mechanical properties of the materials. The structural analysis began with the characterization of the hemp shave cross-section structure. The smaller images show a schematic cross-section of the sample, and the red marking indicates the area where the materials microscopic examination was focused. The cross-sections of hemp shaves in different focuses are presented in Figures 3 and 4.

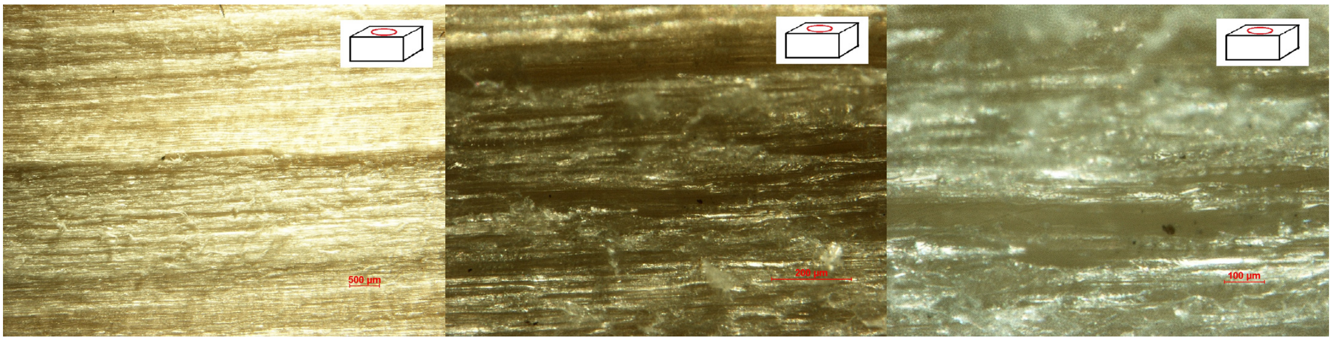
The microscopic images of hemp stems and pine wood reveal significant similarities and differences. Cellular structures in both are complex and provide their mechanical strength and flexibility. The hemp fibers consist of long, thin strands containing cells with thick walls. On the other hand, the rings in pine wood form characteristic rings and transport water. The crumb cells in both materials store nutrients, while the elements that carry water and substances are responsible for transporting them. The ×5 and the ×11.5 magnifications show details of the cell wall structure, including cellulose microfibril layers and cavities between cells. Analyzing these structures provides a better understanding of materials' mechanical properties and suitability.

The study involved drying and shredding fiber hemp and pine biomass, which was then turned into briquettes and pellets. Microscopic analysis was conducted on the resulting products to determine their internal structure. The distribution of individual biomass fragments, three magnifications, 0.75×, 5×, and 11.25×, were applied. These magnifying techniques allowed analysis of both the overall structure of the briquettes and pellets and the distribution of individual fragments. The microscopic images may contain slight blurring in some cases. The microscopic pictures may exhibit slight blurring due to the uneven surface of the pellets and briquettes, resulting from the anisotropic nature of the analyzed material. Despite efforts to achieve a perfectly flat alignment, some unevenness persisted. Pellets and briquettes were observed under the microscope from the front, i.e., from a position that permitted observation of their internal structure, to ensure optimal observation conditions. The pellets from hemp structures in different focuses are presented in Figures 5 and 6.



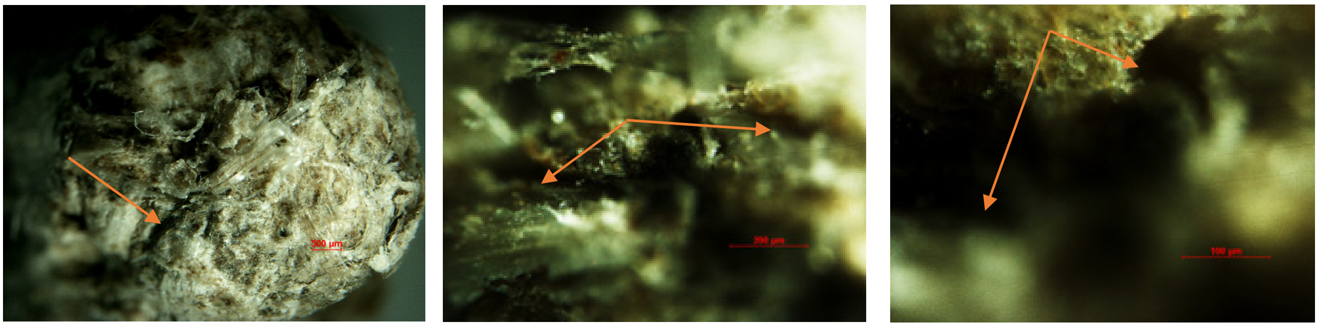
(**a**) (**b**) (**c**)

Figure 3. The hemp shaves cross-sections: (**a**) 0.75×; (**b**) 5×; (**c**) 11.25×.



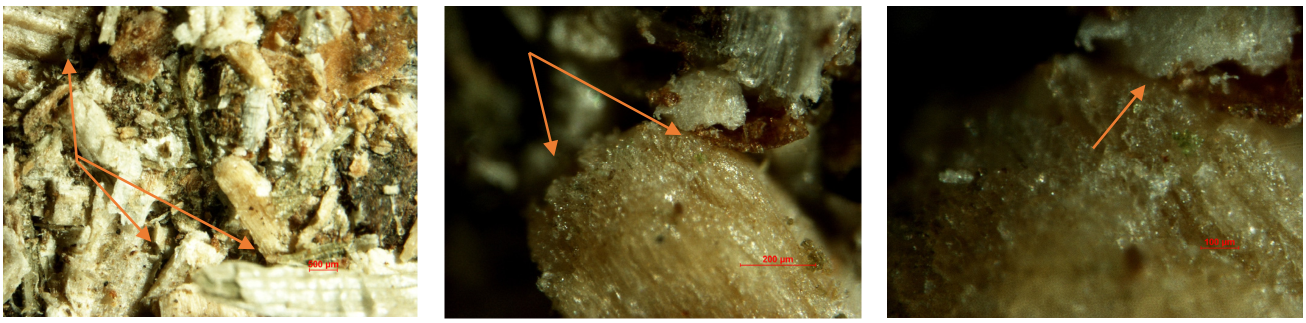
(**a**) (**b**) (**c**)

Figure 4. The pine shaves cross-sections: (**a**) 0.75×; (**b**) 5×; (**c**) 11.25×.



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

Figure 5. The pellets from hemp structure: (**a**) 0.75×; (**b**) 5×; (**c**) 11.25×.



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

Figure 6. The briquets pine structure: (**a**) 0.75×; (**b**) 5×; (**c**) 11.25×.

An analysis of the internal structures of hemp, pine pellets, and briquettes revealed differences. Various approximations, including 0.75×, 5×, and 11.25, ensure accurate representation. The hemp pellet showed different sizes of biomass particles at both 0.75× and 5× magnifications, linked by mechanical bonds when fibers were interlaced and chemical bonds when lignin was present. The nanofibrils of cellulose forming cell walls and lignin filling the spaces between fibers were visible at 11.25× magnification. The pine briquette at 0.75× magnification showed a more homogeneous structure with parallel fibers. An examination of the sample at 5× magnified the porosity and confirmed that lignin was the primary binding agent. It is possible to see coniferous wood cell walls with cellulose microfibrils, cell cavities, and resin ducts at 11.25× magnification. Due to the structure of the image, slight blurring is visible. The image has been corrected to align with these measurements. The overall visual remains informative despite the minor imperfections. A series of arrows illustrate the mechanical connections during the compaction process, emphasizing the structural relationships and interactions within the material.

3.4. Hemp and Pine Shaves Compressive Strength Analysis

3.4.1. Energy Consumption During *Hemp* and *Pine* Compressive Strength Tests

The research focused on hemp (*Cannabis sativa* L.) and pine (*Pinus silvestris*) stems. Briquets or pellets can be innovative and environmentally friendly using hemp shives as a raw material. The study also included pine shives, which are commonly used materials. Static compression tests were conducted on both types of shives. Considering the material's natural characteristics, the structure exhibited anisotropic parameters due to its inherent properties. Natural materials are hygroscopic, which explains why moisture significantly affects their properties. The compression process on a test machine with a plane for compressing samples was determined to take place at an approximate moisture content of about 12%, according to the results obtained. A change in moisture in the material can cause shrinkage or swelling of the material. The material dimensions when moisture levels affect change in the material. Moisture control is one of the most significant parts of testing samples, and it ensures that they were measured correctly and that their mechanical properties were as accurate as possible. Additional material inspections were necessary to ensure samples were kept in proper condition. By the applicable norms, a static compression test has been carried out. An approximate analysis was conducted to determine hemp and pine biomass's moisture and volatile matter contents as well as the ash and fixed carbon contents. Methods for the study were based on the ASTM ISO (International Standards Testing Method) [16].

To provide a broader analytical perspective, the results presented in Figure were compared with findings from the literature. Under optimal moisture conditions, compression strength values of Scots pine (*Pinus sylvestris*) have been reported to range between 100 and 120 MPa along the fibers [23]. The discrepancy between established results for pine (about 100 MPa) and the established range in the literature (100–120 MPa) can be attributed to differences in sample preparation, moisture content, and test methodology. The study used samples with variable densities and moisture levels (approximately 12%) closer to real-world conditions. By contrast, the values cited in the literature typically reflect standardized, ideal conditions, often with lower moisture levels and uniform sample dimensions. According to Placet et al., hemp (*Cannabis sativa* L.) has a compression strength of between 25 and 30 MPa, depending on the humidity conditions [24]. The results obtained in the study (24.3–26.4 MPa) are consistent with these reports, validating our methodology and sample preparation. The consistency validates our methodology. These factors are consistent with findings from prior studies, which highlighted the influence of fiber orientation and structural irregularities on mechanical performance. Differences in density, moisture content, and lignin and cellulose proportions, which significantly influence mechanical properties, can be attributed to the observed variations [25]. The lower elasticity modulus observed in hemp samples shows its inherent flexibility, in contrast to pine wood's higher rigidity. Based on these characteristics, hemp may be a better option for applications that demand flexibility and resilience, while pine remains more appropriate for structural applications that require high compressive strength.

According to the characteristics of all samples, force changes with displacement as displacement increases. In static stretching, hemp samples consumed 0.05 MJ/mm^3, while pine samples consumed 0.08 MJ/mm^3. Estimating how much power is required to tear a specimen requires considering the grade and preparation parameters. The coefficient of determination, more significant than 0.9 in a particular model, was calculated using graphs. To construct the polynomial, we assumed a coefficient of 0.92 or higher. Since the method could not incorporate more accurate results, it could not be successful. Third-degree polynomials can provide mathematical explanations of stretching processes in different samples. The compression test results of the prepared material are presented in Table 2.

Table 2. The integral equations for the total work involved in stretching.

Material	Total Work Carried Out under Specified Conditions $W_{(\tau,\varphi)}$	Determination Coefficient R^2 (SD)	Displacement L (SD), mm	Total Work Involved in Stretching (SD), J
Hemp	$W_{(Native)} = \int_0^{0.001 \cdot l} -1032x^2 + 10,312x$	0.974 (0.006)	6.488 (0.355)	1.5×10^{-4} (1.8×10^{-4}) [a]
Pine	$W_{(HWEIII)} = \int_0^{0.001 \cdot l} 6.334x^6 - 66.216x^5 + 259.35x^4 - 457.49x^3 + 318.22x^2 - 4.294x$	0.975 (0.015)	1.421 (0.449)	1.0×10^{-4} (9.2×10^{-5}) [a]

[a]—homogenous group; SD—standard deviation.

The research results were complemented by statistical analysis to determine the relationship between the type of raw material, the input of power performed, and the compaction required to complete the process. Through statistical analysis, the research findings will be evaluated. Statistical analysis revealed no differences between the parameters measured. According to the study results, $F(1, 7) = 0.222$, and $p = 0.652$ is significant for the statistical expression. According to the Duncan's test, none of the parameters identified individual membership in a homogeneous group. The p-value exceeds the alpha significance level 0.05, indicating homogeneity among all parameters. Accordingly, the variability of the data was consistent across all study groups, regardless of the study material. Test results showed that all parameters could be classified into a homogeneous group, indicating that changing the material did not affect the results significantly. Based on the material may be valuable for various applications due to its stable properties.

The conclusion was further validated by the Mann–Whitney U test, which confirmed the results of the previous ANOVAs. In the Mann–Whitney U test, $p = 0.713303$, which exceeds the alpha level of 0.05, affirms that there was no statistically significant difference between the groups. According to the result, the measured parameters were homogeneous across study groups. Based on these results, it is concluded that the type of raw material does not significantly affect the amount of power required for compaction. Based on their agreement, these findings are reliable and stable, allowing them to be applied to various materials.

3.4.2. The Hemp and Pine Shave Compression Strength Test

The strength properties of selected lignocellulosic materials were compared. Two cross-sections of the base were measured to determine the dimensions of the samples. Hemp was studied by considering its outer and inner diameters ($D \times d$), where the length was measured along two parallel axes. In the tests, stresses occurred due to forces acting on the material in specific ways, with particular attention paid to Young's modulus and energy consumption. Static compressive strength tests of a material were considered complete when the specimen cracked and separated into parts. Calculating the variations in material compression based on the stress or load on the material is possible. The yield stress calculations were complex in all cases studied because they were anisotropic. A problematic aspect of the wood was its anisotropic nature, which presents challenges when determining its homogeneous strength. Young's modulus and energy consumption were used to compare strength properties. Compression and tension should have the same Young's modulus in the proportional limit for the materials. The results of compression tests carried out along the fibers of hemp samples to determine the strength of the native material are presented in Table 3.

Table 3. The results of the hemp and pine shave compression strength.

Material	Plain Dimensions, mm^2	Longitudinal Dimension, cm	Compression Strength Along the Fibers, MPa	Yield Strength [mm]	Determination Coefficient R^2	Elasticity Modulus E (SD), MPa
Hemp	301.440	30	24.306	1.791	0.877	10.540 (0.998) [a]
	298.104	30	25.418	1.917	0.922	
	298.104	30	25.211	1.708	0.882	
	298.104	30	26.410	1.875	0.884	
	298.104	30	26.287	1.242	0.947	
Pine	176.625	35	29.900	0.992	0.946	88.936 (55.121) [b]
	153.860	33	92.788	0.450	0.968	
	153.860	35	39.974	0.467	0.945	
	153.860	22	69.397	0.408	0.977	

[a,b]—homogenous group; SD—standard deviation.

The endurance test results were used to determine the material elastic modulus. Specific findings were applied to determine the yield stress of an anisotropic material. During the compression process of hemp and pine shelves, the yield stress was measured when the first crack appeared. The elastic modulus, E, of both measured materials may be calculated as a trend line adjacent to a function with a coefficient of determination of R^2 that gives the distance from the predicted function determined by the trend line. A material with a moderate elastic modulus matches the accuracy assumption of elastic modulus, and a material with a medium coefficient of determination matches assumption. Based on the R^2 coefficient, the model fits well based on the measurement. The elastic modulus of pine has the highest value, approaching 88.9 MPa. The high standard deviation observed in pine samples can be attributed to several factors. An inherent anisotropy in wood, particularly pine, can cause the mechanical properties of wood to vary depending on which direction the load is applied. The presence of knots and other defects in some of the pine samples may also have contributed to lower strength values. Variations in latewood density within the pine samples may have affected the results. Larger sample sizes and a deeper analysis of wood characteristics could further illuminate the factors contributing to pine strength variation.

The results were tabulated with a statistical analysis to measure the difference in the elastic modulus, E, of tested materials in addition to the tabulated results. The studies showed no statistically significant differences between the parameter measurements. According to the statistical analysis, the results are meaningful since the degree of significance $p = 0.014$, and the empirical statistic $F(1, 7) = 10.484$ indicates that the results are significant. Duncan's post-hoc test was used in the statistical analysis to assess the homogeneity of variance. The test is crucial for determining whether the variability in each group is similar, which is a fundamental assumption of many statistical analyses, including the ANOVA. Duncan's test showed statistical differences between the parameters, dividing marginal means into two homogenous groups. It was also noted that model fit differences (R^2) between materials were due to an elliptical shape of the graph in the initial phase. Based on the low fit here, it is likely that the model needed to reflect the material's behavior during initial loading fully. Considering that Young's modulus is a parameter determined in the elastic range, its value may change as the load increases before the material transitions into plasticity.

Furthermore, the Mann–Whitney U test validated Duncan's test and ANOVA results as a nonparametric alternative for comparing independent groups. The p-value for the test was 0.019965, below the alpha significance threshold of 0.05, indicating statistically significant differences between the tested materials. Accordingly, the elastic modulus, E, differs significantly between the studied materials according to the ANOVA ($p = 0.014$) and Duncan's tests. Multiple statistical methods have consistently found similar results, highlighting the robustness of the observed differences and the significance of accounting for initial loading effects. Results show that material type influences elastic modulus values significantly, particularly during early compression stages.

3.5. The Briquets and Pellets Moisture and Durability Analysis

The moisture content is among the most important factors affecting products from hemp and pine [4,6]. The hygroscopic properties of naturally occurring lignocellulosic materials influence all of their properties. After harvest, natural material typically contains a large amount of water, which needs to be dried under controlled temperature and ventilation conditions. It is important to maintain the optimal moisture level in the material to maintain its flexibility. In accordance with the methodology, compression is performed on a test machine using a specially prepared compression tube. Before all tests, moisture samples were analyzed. The pellets and briquettes were tested at a moisture content of approximately 7%. The results of the moisture content of samples are presented in Table 4.

Table 4. Content of Non-Combustible Mineral Matter, %.

Biofuel	Sample Weight, g	Moisture Content, %	Mean Moisture Content (SD), %
Pellets	2.24 2.14 2.07	6.72 7.29 7.30	7.11 (0.33) [a]
Briquettes	21.63 9.27 6.57	6.78 6.96 6.87	6.87 (0.09) [a]

[a]—homogeneous group; SD—standard deviation.

The following table shows the moisture content percentages of biofuel pellets and briquettes. The moisture content of pellets and briquettes ranges from 7.11% for pellets to 6.87% for briquettes. A statistical analysis and the Duncan's test support the conclusion that the measured parameters had significant variation. Compared to pellets, briquettes seem to have a slightly lower water content. The moisture content of pellets and briquettes varies widely between samples, suggesting a quality difference between their productions. The production was prepared based on moisture content to ensure proper pellet and briquette parameters. According to the methodology, the sample was conditioned to 12% moisture in a conditioning chamber.

The Mann–Whitney U test and Duncan's statistical analysis were used to validate the results, as initially stated. The Duncan statistical analysis will validate the results and initial stats. It was found that the p-value of the test was 0.662521, which is higher than the alpha significance threshold of 0.05. The results indicate no statistically significant differences in moisture content between pellets and briquettes. Based on the Mann–Whitney U test, it can be concluded that there were slight variations between pellets and briquettes (7.11 percent for pellets and 6.87% for briquettes), but these differences are not statistically significant. The consistency between both statistical methods illustrates the robustness of the results. Based on the results, it can be concluded that there is no meaningful difference between the two types of biofuels in terms of moisture content. The observed quality differences in production are likely to be due to factors other than moisture content alone.

The study also evaluated the mechanical durability of briquettes and pellets regarding their production process. Raw material was obtained from previously prepared material to produce the briquettes and pellets. The material was prepared by drying and grinding it to achieve the desired result. The drying process was performed with a chamber dryer, and the shredding was carried out with a flail shredder. Briquettes and pelleting were performed on the shredded product using dedicated industrial equipment. The mechanical durability of the developed research product was evaluated to determine its suitability for further use. The prepared pellets and briquettes from hemp and Scotch pine are presented in Figure 7.

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

Figure 7. Material: (**a**) pellets from hemp, (**b**) briquets from Scots pine.

According to the established research methodology, hemp pellets and pine briquettes were subjected to durability tests. Both materials were analyzed regarding the prevailing process parameters, such as temperature and humidity, to determine their mechanical durability and resistance to external factors. The study results allowed an assessment of the impact of varying environmental conditions on the durability and stability of pellets and briquettes, which is essential for their practical use and storage [26]. The study also had to compare the results with literature studies [27] to assess the consistency and reliability of the data.

The results of the study were to calculate the average durability factor, Ψ. Based on the assumed material and process parameters, the average durability factor of pellets and briquettes produced from shredded hemp and pine residues is presented in Table 5.

Table 5. The average durability factor of pellets and briquettes from hemp and pine.

Products	Material Moisture, %	Durability Factor Ψ
Hemp	12.0	0.98 (0.01) [a]
Pine	12.0	0.45 (0.13) [b]
Pine *	10.0	0.19 (0.04) [c]
	15.0	0.17 (0.01) [c]
	20.0	0.10 (0.03) [c]

*—literature results; [a,b,c]—homogenous groups; SD—standard deviation.

In comparison with briquettes, pellets exhibited a greater degree of durability. Two different materials were used during the compaction process, which might have affected the bond between raw materials. The hemp fiber is entangled with other fibers in a pattern that results in a mechanical bonds. Local plasticization and the subsequent solidification of resins in the briquette material appear to be the primary causes of pine structure bonds. For hemp pellets, the highest durability coefficient was 0.98. Among the products, the standard deviation for the average durability values varied, with a concentration of 0.01% for pellets and 1.3% for briquettes, resulting from the wide spread between the durability coefficient values. The results were statistically analyzed to determine the validity of increasing the temperature of the briquetting process and the effect of raw material moisture content. The durability coefficient of pellets and briquettes based on the moisture content was compared using a one-way ANOVA analysis of variance. The effects of statistical analysis on the durability factor of pellets and briquettes with different moisture contents are presented in Figure 8.

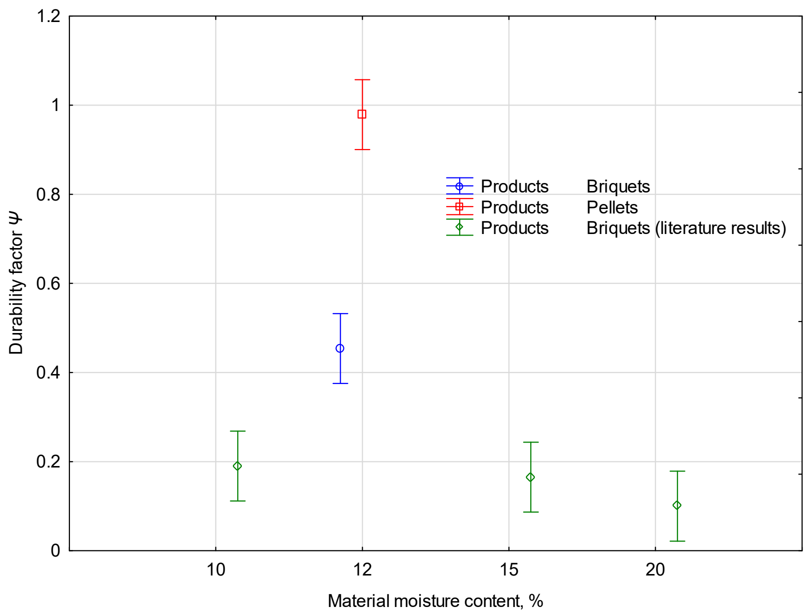


Figure 8. The effects of statistical analysis on the durability factor of pellets and briquettes with different moisture contents.

An analysis of the ANOVA results was further validated using the Mann–Whitney U test, a nonparametric comparison method. The Mann–Whitney U test yielded a *p*-value of 0.080857, which exceeds the alpha significance level of 0.05. Despite the low statistical significance of the *p*-value, it indicates a marginal but not definitive difference in durability coefficients between pellets and briquettes based on the ANOVA. Pellets exhibit higher durability than briquettes, as evidenced by the consistency of results across both statistical tests. The lack of strong statistical significance ($p > 0.05$) suggests that while a measurable difference exists, it cannot be attributable solely to moisture content. There may be a need for additional research on temperature, raw material composition, and mechanical properties to fully explain the observed durability differences. According to these findings, pellets' higher durability may be due to more effective bonding mechanisms, particularly hemp-based products.

The statement compares the durability results of our briquettes and pellets with the briquettes described in the literature [26]. The effect of material type and moisture content on the durability of the briquettes showed partial differences between study groups. Compared to the 10–15% moisture range, moisture content did not significantly affect the durability of pine briquettes, where the durability coefficient, Ψ, averaged 0.17, ranging from 0.19 for 10% moisture content to 0.17 for 15%. Hemp pellets showed significantly higher durability Ψ = 0.98 ± 0.01 compared to pine briquettes Ψ = 0.45 ± 0.13 at the same moisture content of 12%. Results obtained with pine briquettes differ from literature data [28,29], where the Ψ factor ranged from 0.10 for 20% moisture content to 0.19 for 10% moisture content. Durable differences can be attributed to factors such as the type of raw material and the production method. Hemp pellets with durability coefficients near 1.3 indicate their potential as a biofuel with high durability and mechanical strength.

3.6. The Residual Mineral Content After Combustion Content Analysis

The evaluated biomass samples were chemically analyzed to determine their fundamental properties. As part of this analysis, we determined the chemical composition of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S), as well as the amount of mineral residue left after combustion. The ability to assess the potential of biomass as a renewable energy source and its impact on combustion efficiency and emissions depends on understanding these parameters. Materials have varying elemental compositions, affecting their energy potentials and combustion characteristics. Compared to pine, hemp biomass had a slightly lower carbon content, which indicates a lower calorific value. It was found, however, that both materials had comparable levels of hydrogen and oxygen, suggesting a similar combustion process. Nitrogen levels were notably higher in hemp, contributing to NOx emissions, while sulfur levels were consistently low throughout all samples, reducing SO_2 emissions and corrosion risks. The results of the chemical composition analysis, including residual mineral content, are presented in Table 6.

Table 6. Chemical composition and residual mineral content of hemp and pine biomass samples.

Material	C, %	H, %	O, %	N, %	S, %	Average Residual Mineral Content After Combustion (SD), %
Hemp	48.12	5.85	43.05	0.78	0.12	2.32
Pine	50.43	5.71	41.50	0.42	0.10	2.93

To understand the thermal behavior of these biomass sources, observing the differences in elemental composition is essential. A higher carbon content in pine leads to a higher energy yield per unit mass. In comparison, a higher nitrogen content in hemp could increase NO_x emissions, requiring attention in combustion applications. The pine may depose more ash due to its higher residual mineral content, posing operational challenges during thermal conversion. The study also determined how much ash is present in hemp and pine samples. As part of the experiment, samples were placed in crucibles and burned in a muffle furnace. An analytical balance was used to weigh the residual ash after cooling the samples in a desiccator, determining the residual mineral content after combustion. The residual mineral content after combustion can reflect the process of densification, which is crucial for analyzing the chemical composition of the material. A summary of the residual mineral content after combustion analysis is presented in Table 7.

Table 7. A summary of the residual mineral content after combustion analysis.

Material	Average Ash Weight (SD), g	Average Residual Mineral Content After Combustion (SD), %
Hemp	0.026 (0.003) [a]	2.32 (0.63) [a]
Pine	0.029 (0.012) [a]	2.93 (1.22) [a]

[a]—homogenous groups; SD—standard deviation.

An analysis was conducted to determine how much ash is present in hemp and pine materials. This study aimed to compare the residual mineral content after the combustion of different material samples. A statistical analysis was performed to explore the relationship between residual mineral content after combustion and the type of material. Based on the statistical analysis, no significant differences were found between the measured parameters, with an effect value of $F(1, 10) = 1.1944$ and a significance level of $p = 0.30007$. Based on the tests conducted, the univariate ANOVA analysis represented the relationship between material type and residual mineral content after combustion. The statistical relationship between material and residual mineral content after combustion is presented in Figure 9.

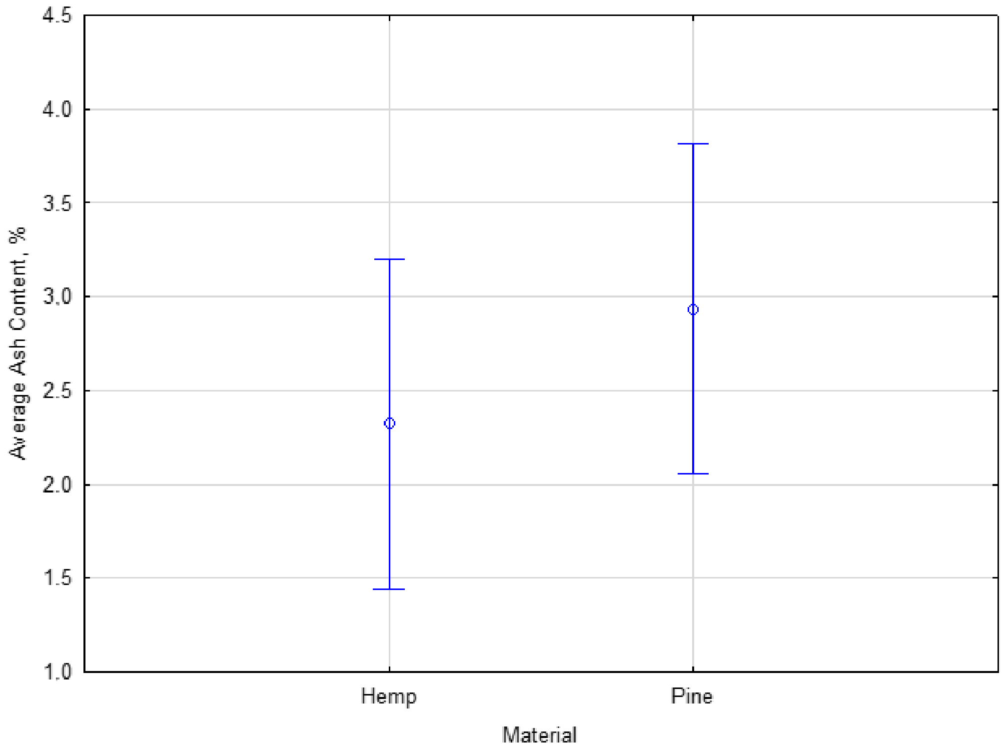


Figure 9. Statistical relationship between material and residual mineral content after combustion.

A statistical analysis examined the materials' residual mineral content after combustion. According to Duncan's test, there was no statistically significant difference between the materials regarding residual mineral content after combustion (%). The post-hoc analysis showed that all materials belonged to one statistically homogeneous group. No significant differences were found between them. The p-value was above 0.5, meaning there were no significant differences.

The residual mineral content of biomass after combustion provides valuable information on the inorganic structure. Still, slagging and fouling pose operational challenges in high-temperature industrial combustion systems, where detailed oxide composition analyses are typically required. Although such concerns are less critical in small-scale thermal applications, this study focuses on the essential characterization of raw biomass. After combustion, moisture content, volatile matter, fixed carbon, and residual mineral content comprehensively evaluate fuel properties. The properties of the solid residue after combustion vary considerably between energy conversion systems concerning combustion conditions, operating temperatures, and air-to-fuel ratios. The study does not examine ash fusion behavior or high-temperature industrial processing, so a detailed oxide composition analysis is inappropriate. The results presented here align with standard biomass fuel assessments and are suitable for assessing densification and small-scale combustion applications.

4. Discussion

The innovative environmental solutions have investigated the factors influencing the compaction process and durability of pellets and briquettes produced from shredded hemp and pine logging residues. Mechanical strength is a crucial characteristic of biofuels, impacting their production, handling, storage, and utilization. Greater mechanical strength enhances durability during transport and storage, minimizing breakage and degradation losses. Furthermore, stronger biofuels can exhibit improved combustion efficiency and reduced emissions. Optimizing compaction parameters can tailor the mechanical strength of hemp and pine biofuels, subsequently influencing other key properties such as heat of combustion, residual mineral content after combustion, and moisture content. The analysis provides valuable insights. Further research is needed to fully elucidate the complex interplay between mechanical strength and other biofuel characteristics. Consideration of mechanical strength is essential for the development and optimization of sustainable bioenergy technologies.

The research on the anisotropic nature and irregular composition of lignocellulosic materials directly affects their compaction and mechanical properties [30]. Results indicate that hemp is more durable and compressive than pine, which can be attributed to several factors. Hemp has a higher cellulose content and a lower lignin content, which makes it more flexible and capable of forming stronger bonds during compaction. Microscopic analysis of hemp pellets and pine briquettes showed that they exhibit the ability to form mechanical bonds. There may be a difference in bonding mechanisms between hemp and wood pellets, which may explain their higher durability. A lower moisture content in hemp pellets may also increase their durability compared to pine briquettes. The findings suggest that hemp has significant potential as a source of sustainable and efficient biofuels.

The study shows that moisture content significantly impacts compaction efficiency and durability. In hemp and pine, 12% moisture content improved durability by 15% compared to 8%, matching findings for fallen leaf pellets, where optimal moisture levels (15%) resulted in durability of 96.68%. The literature reported that tensile strength and bulk density decreased from 250 kPa to 225 kPa at higher moisture levels (20%). The increase in elasticity, which rose to 2.35 mm from 0.75 to 0.75 mm, enhanced transport resilience [31]. In contrast to similar studies, a direct comparison of hemp-based biofuels under optimal moisture conditions [31] indicates consistent trends. Consistent with prior studies, the optimal moisture content for such materials was identified as approximately 12%, ensuring high-quality compaction and product stability [27,32,33]. Maintaining the moisture level minimizes structural inconsistencies and enhances durability during storage and use.

In the materials studied here, cellulose, hemicellulose, and lignin comprise most of the lignocellulosic material. A cellulose molecule consists of long chains of glucose molecules, a hemicellulose molecule consists of various sugar units, and a lignin molecule consists of complex polymers. There can also be many available cellulose and polysaccharides in lignocellulosic materials [3]. Materials with strong bonds tend to be more durable and resistant to mechanical damage. The range presented was compared with values found in the literature, confirming the validity of the quality of pellets and briquettes. Studies of similar plant materials have shown that the compacted fraction has lengths of 1.8, 5, 10, and 15 mm [34]. The findings align with prior observations on lignocellulosic materials, showing that materials with greater stiffness and resistance to deformation, such as hemp, exhibit higher elastic modulus values [22,35,36]. As hemp and pine biomass contain hemicellulose, the compaction process and the resulting biofuels' properties may be affected. A binder like hemicellulose can enhance particle cohesion during compaction. The combustion of hemicellulose can contribute to the energy yield of the biofuel.

The static compression tests [37] further revealed the inherent anisotropy of the materials, with variations in compressive strength and elastic modulus depending on the anatomical direction of load application. The anisotropy explains the differences in strength along the longitudinal, tangential, and radial axes of lignocellulosic samples, with compressive strength for wood samples ranging from 100 to 120 MPa along the fibers. Defects such as knots and rot significantly reduce material strength, sometimes by as much as 50 MPa [10,38]. Knots disrupt the uniformity of fibers, creating stress concentrations and structural discontinuities that weaken the material. Depending on the intended use, knots can also negatively influence the aesthetic appeal of the wood, creating visually interesting patterns or detracting from a uniform appearance [39]. Wood that contains knots may experience significant drying difficulties, potentially resulting in warping or cracking [40].

Despite these insights, the study has certain limitations. The sample size for compression testing was relatively small, which may restrict the statistical robustness of the findings. Additionally, environmental conditions during testing, such as temperature and humidity, were controlled but may not fully replicate real-world conditions where such materials are used. Furthermore, while the study highlights the impact of knots and defects on material performance, the specific influence of varying defect sizes and distributions was not comprehensively analyzed. These limitations highlight areas for further research and refinement of the experimental approach.

The study provides valuable empirical support for using logging residues and forest biomass as sustainable energy resources. Biofuels can be produced and utilized more efficiently using hemp pellets since their superior durability and compressive strength are a stronger alternative to pine briquettes. As a result, transportation and storage costs could be reduced, and combustion efficiency could be improved. While the energy balance was not explicitly calculated, the research highlights the potential of hemp and pine residues as renewable biofuel sources, aligning with global sustainability goals. The study supports the broader adoption of renewable energy technologies by transforming forest and agricultural waste into durable pellets and briquettes. The comparison of the compaction process and product durability with existing literature shows promising applications for hemp biomass, which demonstrated higher durability coefficients compared to pine. These results suggest that hemp could be a viable alternative to traditional wood sources, providing a renewable and efficient material for energy production.

The energy consumption during the compaction process was also examined, revealing differences between hemp and pine. The compaction of pine requires more energy because of its density and stiffness, requiring more force to achieve the same degree of densification. Biomass moisture content and chemical composition influence compaction behavior and final biofuel properties. Compaction may be enhanced by hemp's lower moisture content, high cellulose, and low lignin content, as well as better flexibility. The findings highlight the importance of considering energy consumption, moisture content, and chemical composition when optimizing compaction parameters for various biomass types.

The heat of combustion of hemp (*Cannabis sativa* L.) was analyzed based on literature data for samples with 18% moisture content and 0.25 mm fraction fineness. Kołodziej et al. reported the heat of combustion for hemp panicles, straw, and whole plants as 19.8 MJ/kg, 17.9 MJ/kg, and 18.8 MJ/kg, respectively [41]. These values align with data obtained by other authors, who reported a calorific value for hemp ranging from 17.5 to 19.24 MJ/kg [42,43]. Researchers have conducted separate heat of combustion studies for different parts of hemp sativa. The highest calorific value was recorded for hemp panicles. The observation is relevant when hemp is grown for textile purposes. In other cases, however, there is no economic justification for separating the panicles from the straw and using them for energy production. Therefore, when whole hemp plants are grown for energy purposes, the percentage of panicles in the total mass may affect the overall energy value of the hemp crop. Mujaba et al. reported similar energy consumption values for similar lignocellulosic materials, suggesting that hemp and pine are equally energy efficient in biofuel production [44].

The heat of combustion reported here for hemp places the crop among other biomass sources with the highest calorific value [45,46]. Kraszkiewicz et al. report the following properties of hemp biomass with a moisture content of 10.98%, heat of combustion of 18.09 MJ/kg, calorific value of 16.64 MJ/kg, volatile matter content of 69.63%, and residual mineral content after combustion of 2.51%, and the elemental composition is also reported: carbon content 43.4% and sulfur 0.06% [47]. Gravalos et al., in their study of pine (*Pinus sylvestris*) with a moisture content of 24.59%, achieved an average gross calorific value of 14.59 MJ/kg and a residual mineral content after combustion of 0.64% [48]. In comparison, Saha et al., who tested pine wood at a lower moisture content (7.78%), obtained the following mean values: carbon 49.8%, nitrogen 0.17%, sulfur 160 ppm, gross calorific value (GCV) 19.56 MJ/kg, and residual mineral content after combustion 2.24% [49].

According to the proximate and ultimate analysis of hemp biomass, it contains more volatile matter and less ash than pine biomass [50,51].

The higher reactivity and lower ash formation suggest that hemp can be used for combustion applications. The content of non-combustible mineral matter in biomass can influence the combustion process and the properties of the resulting biofuels. Higher mineral content can increase ash formation during combustion, affecting energy conversion efficiency and potentially causing fouling or slagging in combustion systems [50]. It was necessary to research because there was a gap in understanding the mechanical properties of lignocellulosic biomass, namely hemp and pine. Although these materials have been extensively studied for biofuels, no well-documented studies have been conducted on their behavior under pelletizing pressure. Researchers used a unique approach to compare hemp with pine, contributing to a broader understanding of using lignocellulosic biomass in renewable energy. In addition to improving the mechanical properties of hemp, optimizing moisture content, and improving microscopic structure and bonding, discoveries are transforming our understanding of hemp. The discoveries provide valuable information on how hemp and pine residues can be used as renewable resources. These studies aim to understand better these materials' structural properties, material properties, and compressive strength, especially those related to biofuel production.

5. Conclusions

During laboratory tests and statistical analyses, it was found that briquette density and durability are influenced by the parameters of the technological process, especially the pressing force. It has been found that hemp pellets form mechanical bonds during compaction because of fibers entangled in each other. Other types of biomass than those used in this study also contain lignin, but the higher cellulose content and lower lignin content of hemp may contribute to its relatively higher ability to form more permanent bonds during compaction.

Assessing the structural integrity of wood materials to improve energy efficiency can be performed by, among other things, testing their mechanical properties, strength tests, and microscopic analysis. The study evaluates the suitability of hemp and pine biomass for bioenergy by integrating ultimate (CHNS), proximate (moisture, volatile matter, fixed carbon, and residual mineral content after combustion) analyses. Oxide composition and mechanical strength analyses can provide additional insight for high-temperature industrial systems but not for small-scale raw biomass characterization. The selected methods align with standards for assessing biomass fuels, ensuring the results are relevant and transferable to energy and biofuel production.

The results of testing pellets with a diameter of 6 mm and a length of 10–25 mm revealed significant differences. The average durability factor of hemp pellets was more than twice as high (117.78%) as that of pine briquettes. The difference was due to the 15.79% higher compaction capacity of hemp pellets than pine briquettes. Fiber entanglement and compaction are mainly responsible for mechanical bonding in hemp pellets. This effect is enhanced by the presence of lignins and other organic compounds. Adequate moisture content was the key to producing briquettes with high durability. Increasing the moisture content of the materials from 8% to 12% resulted in a 15% increase in durability.

The compressive strength tests demonstrated that hemp pellets withstood an average force of 2.5 kN (maximum 3.1 kN), while pine briquettes failed at a lower force of 1.8 kN (maximum 2.3 kN). These results were directly related to the density differences in the materials. The hemp pellets had a density of 1100 kg·m^{-3} compared to 950 kg·m^{-3} for pine briquettes. These findings highlight the potential of hemp biomass as a superior alternative for biofuel production. By optimizing moisture content and leveraging hemp's structural advantages, biofuel production can achieve greater efficiency and sustainability.

Author Contributions: Conceptualization, K.R., W.J.W. and G.M.; methodology, K.R. and G.M.; software, K.R. and G.M.; validation, K.R. and W.J.W.; formal analysis, K.R. and W.J.W.; investigation, K.R., W.J.W. and G.M.; resources, K.R. and G.M.; data curation, K.R. and W.J.W.; writing—original draft preparation, K.R. and W.J.W.; writing—review and editing, K.R., W.J.W. and G.M.; visualization, K.R.; supervision, K.R.; project administration, K.R.; funding acquisition, K.R., W.J.W. and G.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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