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Article

The Source of K Fertilizer for Industrial Hemp (*Cannabis sativa* L.): Mechanical and Chemical Properties of Stem for Rammed Earth Walls

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Abstract: Industrial hemp, as a natural plant fiber, has received increased research attention recently. Potassium fertilization is one of the most important fertilizers for plant stem thickness, but how the formulation of K fertilizer influences stem morphology and stem tensile strength remains unclear. This study aims to examine the influence of K fertilizer sources on industrial hemp stem properties, with a specific focus on the fibers, to evaluate their potential applications as reinforcement material for stabilizing rammed earth in sustainable construction. A field experiment was set up with different K fertilizer types applied as pre-sowing fertilizer in the following doses: K_0—control, K_1—100 kg ha^{-1} KCl, and K_2—100 kg ha^{-1} K_2SO_4. Different K fertilizations did not have significant influence on stem height, which was on average 71.2 cm, nor on stem diameter, which was on average 3.4 mm. Regarding the macronutrient content of the industrial hemp stem (N, P, and K), K fertilization treatment significantly influenced ($p < 0.05$) their accumulation. The N, P, and K content in the stem within fertilization treatment averaged 0.78, 0.72, and 1.26%, respectively. The average content of cellulose, hemicellulose, and lignin was not significantly different in relation to K fertilization treatments. In the stem, dry weight cellulose content varied from 57.8% (K_0) to 59.0% (K_1), hemicellulose from 11.0% (K_2) to 11.6% (K_0 and K_1), and lignin from 10.2% (K_2) to 10.5% (K_0). The tensile strength and Young's modulus of the industrial hemp stem were non-homogenous within K fertilization treatments. The highest tensile strength (388.52 MPa) and Young's modulus (32.09 GPa) were on K_1 treatment. The lowest industrial hemp stem tensile strength was determined at K_2 treatment (95.16 MPa), whereas stems in the control treatment had the lowest Young's modulus (21.09 GPa). In the mixtures of hemp fibers with rammed earth, the higher compressive strength was determined on cubic samples than on cylindrical samples. This study contributes to the industrial hemp K fertilization of the newer genotypes, but there has been a lack of research in recent times. Since industrial hemp has great potential in various industry branches, this study also contributes to using fiber extracted from the stem in eco-friendly and renewable forms in mixtures with rammed earth.

Keywords: industrial hemp; potassium fertilizer; KCl; K_2SO_4; morphology; fiber; stiffness; tensile strength; earth mixtures

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1. Introduction

During the past decade, interest in growing industrial hemp has increased rapidly. Industrial hemp is a crop with huge potential and uses. This is mainly due to its seed, which is cold-pressed into quality oil, but also due to numerous phytochemicals of the female plants' inflorescences that can potentially positively affect human health [1–4]. Since ancient times, industrial hemp has been used in folk medicine. This is mostly due to plants rich in phytocannabinoids which naturally occur in *Cannabis* sp. [5]. THC (delta-9-tetrahydrocannabinol) is the most known phytocannabinoid in industrial hemp, which is the major discriminant factor, even though its level is less than 0.3% or 0.2%, mostly in the inflorescence [6,7]. Except for THC, the non-psychoactive compound CBD (cannabidiol) content is desirable in the plant. It has been found that CBD can have therapeutic potential as an antipsychotic, in antiepileptic treatment, and for epilepsy [8–10]. In Italy, Beleggia et al. [11] accentuated that the biological compound content significantly ($p < 0.001$) depends on the genotype and environmental interactions. The authors found that CBD (cannabidiol) is the most abundant, representing 85.1–89.4% of all the cannabinoids, whereas, from total terpenes, the β-caryophyllene α-humulene and α-pinene count for 42–66% of the total terpenes in the inflorescence. Except for cannabinoids, the other compounds have plant-specific value in medicinal use. Barčauskaitė et al. [12] reported that in the Nordic–Baltic region, the total phenolic content of six genotypes was from 6.55 to 12.39 mg/gRUE and the total flavonoid content was from 2.52 to 4.74 mg/gRUE. Industrial hemp is a nutrient-dense plant that offers a wide range of health benefits. Rizzo et al. [13] state that industrial hemp seeds and oil are particularly valued for their high content of healthy fats (including omega-3 and omega-6 fatty acids), protein, fiber, and various essential vitamins and minerals. Hemp-based products such as hemp seeds, hemp protein, and hemp oil benefit overall health, including heart, digestion, and skin health.

The cultivation and processing of industrial hemp stems has a long tradition in Croatia [14,15], especially in lowland regions. Hemp stems consist of several layers, with the bast fibers (outer part of the stem) being the most valuable for fiber production. The fiber is extracted from the bast (outer) layer of the hemp stalk, which is primarily composed of cellulose, hemicellulose, lignin, and pectin [15,16]. The stem of industrial hemp contains 25–30% of fiber [17,18], so it is traditionally used for sails, sacks, nets, and various items for everyday use (cloth, towels, tablecloths, bed linen). The wooden part of the stem that remains after extracting the fiber, hurds, and shieves is used in the paper industry, in construction as a heat and sound insulation material [19–21], and, in combination with cement, for its high resistance to moisture [22]. The varieties used for industrial fiber production are typically low-THC, fast in vegetative growth, erect, and can reach 3–5 m long. Salentijn et al. [23] stated that industrial hemp might potentially yield 25 t ha^{-1} above-ground dry matter and 20 t ha^{-1} stem dry matter.

The changes in the regulations from 2019 [24] give a whole new aspect of using industrial hemp, so it is no longer used only for seed production [25]. The whole plant can be used, so this approach is precious. With these changes, the law enables the use of all parts of the hemp plant for industrial purposes: in textiles, construction, food, the cosmetics industry [26], the car industry [27,28], the paper industry [29], and in biofuel production [30]. Anthropogenic activities can lead to the accumulation of toxic pollutants (heavy metals, radionuclides, and organic pollutants) and burden the production capacity of the ecosystem because soil often receives, binds, and retains harmful substances [31–34]. Thus, industrial hemp can be used as a phytoremediation plant, an environmentally acceptable technology [35]. Industrial hemp can be used in construction, whether in buildings with hemp and lime [36] or mixtures with earth [37].

Macronutrients (N, P, and K) are important in the plant development and yield of industrial hemp stem and seed [38]. Wylie et al. [39] reported that industrial hemp fertilization ranges from 60 to 200 kg N ha^{-1}, from 30 to 120 kg P ha^{-1}, and from 40 to 200 kg K ha^{-1}. Increasing the N fertilization rate positively impacts industrial hemp growth, stem biomass yield, and dry matter weight [40–44]. There are limited investigations into P and K fertilization in industrial hemp production. Due to the potential influence on quality parameters or final yield, potassium fertilizers of different forms were the aim of many studies. The effect of different types of potassium fertilizer (KCl or K_2SO_4) on plant growth, quality parameters, and yield has been the focus of many studies, e.g., for flowering Chinese cabbage [44], potato tubers [45–47], olives [48], sugar beet [49], and other crops. For some other field crops, such as potatoes, chloride reduces tuber yield, dry matter, and specific gravity, so sulfate was superior to the chloride form for potato production [45]. Industrial hemp is assumed to be chloride sensitive, especially if grown for fiber because chloride can cause fewer quality fibers from the stem [50].

Rammed earth is a traditional building technique that has regained popularity in recent decades due to its low ecological impact. However, due to its strength properties, its applicability in the modern normative system is still debatable in most of the world. Researchers strive to increase the strength properties by mixing the soil material with natural or artificial additives. Artificial additives, such as cement, have proved to increase strength properties in a great matter [51–54]. However, the environmental impact should be considered as well. Therefore, researchers have investigated using natural additives (i.e., plant fibers) to aid rammed earth elements' strength and durability properties. Moreover, adding fibers influences the reduction in shrinkage cracks [55–57]. Fibers and vines were also recognized in rammed earth houses in eastern Croatia. According to locals, fibers were added to reduce cracks in the wall, while vines between layers served as a primitive reinforcement in those empirically built houses. The longitudinal compressive strength of hemp stems is important for determining whether hemp stems (or shives) are used as reinforcement for various materials [58]. Therefore, in this study, plants for stem stiffness and tensile strength were collected in the stage of seed maturity.

To use sustainable materials, but also in terms of environmental protection and the use of natural materials, industrial hemp has large potential. Very few authors have reported on the fertilization of industrial hemp. Thus, this study aims to analyze the influence of pre-sowing potassium fertilization on industrial hemp stem morphology parameters, stiffness, chemical properties, and fiber from stems incorporated in rammed earth.

2. Materials and Methods

2.1. Field Trial

A field experiment was set up on the Tenja experimental site of the Faculty of Agrobiotechnical Sciences Osijek, Osijek, Croatia (45.5139, 18.7856). The pre–crop was corn, and the basic cultivation was conducted to a depth of 25–30 cm during November 2020. In the spring of 2021, the winter furrow was closed, after which further supplementary soil cultivation was started to create an optimal seeding layer.

Immediately before sowing, pre-sowing fertilization with different potassium fertilizers was performed to determine whether the formulation of potassium fertilizer affects the morphological properties of the stem and the chemical composition and fibers in the stem of industrial hemp. Pre-sowing potassium fertilization was conducted as K_0—without pre-sowing fertilization, K_1—100 kg ha^{-1} potassium chloride (KCl), and K_2—100 kg ha^{-1} potassium sulfate (K_2SO_4). Fertilization was carried out in three repetitions according to a completely randomized experimental design (RCBD) (Figure 1).

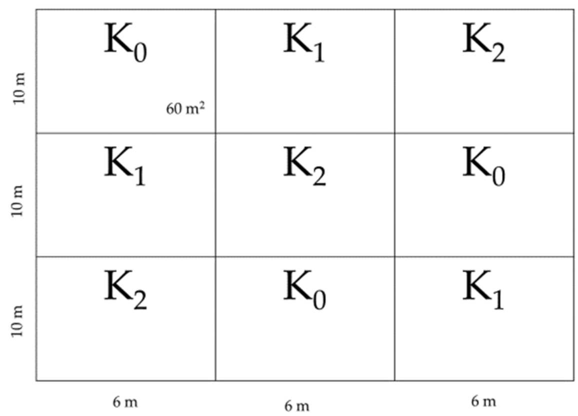

Figure 1. The experiment fertilizers set up.

The variety Finola (the University of Kuopio and Palkkila Farm, Finland) was sown on 17 May 2021 using a pneumatic seeder at an inter-row spacing of 25 cm and a depth of 4 cm, at a seeding rate of 35 kg ha^{-1}. The emergence of industrial hemp was satisfactory, and the plants developed well in the initial stages of growth. Mechanical weed control was carried out on two occasions during the growing season in the early stages of weed development.

2.2. Weather Data

According to the data of the State Hydrometeorological Institute [59], in 2021, during the growing season of industrial hemp, air temperatures were slightly higher than the long–term mean (LTM) with a lower amount of rainfall, which is not conducive to the optimal development of industrial hemp stems (Figure 2). Air temperatures in June were 18% more than the LTM, along with the lack of rainfall in June 2021 (only 18 mm).

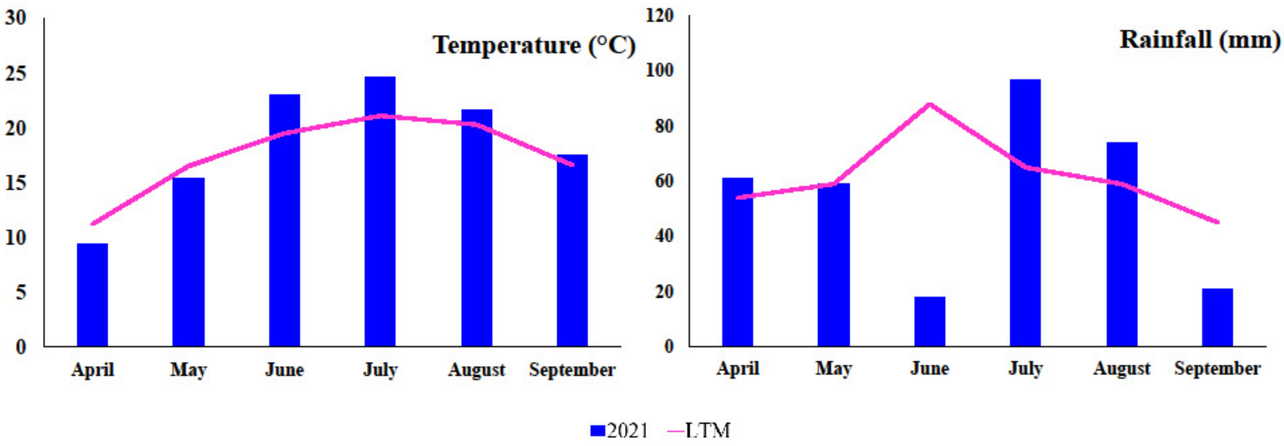

Figure 2. Average air temperature (°C) and monthly amounts of rainfall during the growing season with a long–term mean (LTM) 1961–1990 for the station Osijek [59].

2.3. Industrial Hemp Harvest and Stem Morphology Analysis

The number of plants per unit area was determined just before harvesting the plants. Industrial hemp plants of the Finola variety were harvested to determine morphological parameters on 27 July 2021 from all fertilization treatments. Ten industrial hemp plants were randomly collected from the middle rows of the plots of each fertilization treatment to determine the thickness of the industrial hemp stem. At the time of harvest, the stems of the female plants were still green and inseminated, and the male industrial hemp plants were golden brown. After taking the samples from the hemp fertilization treatments, the samples were transported to the Standardization Center of the Faculty of Agrobiotechnical Sciences, Osijek.

The height of the stem (cm) and the diameter of the stem (mm) were determined. From agronomic parameters, seed mass per plant (g) was determined after cleaning seeds manually from the inflorescence of each plant collected. The total height of the stem was determined using fluorescence and is expressed in centimeters. Stem thickness measurements were performed using a precision digital caliper. The thickness of the stem of industrial hemp decreases towards the top of the stem. Due to the uneven profile and greater or lesser hairiness of the stem, a single place for measuring the thickness of the stem could not be determined. Still, the thickness of the stem was determined for each internode separately, and the thickness of the stem was obtained from the average of all of the internode thicknesses. According to Pasković [50], the stem thickness is measured for each internode separately, 2 cm above the lower and 2 cm below the upper internode. In both locations, the measurement is performed twice so that four measurements are performed at each internode. The average thickness of the stem was calculated from the average thickness of all internodes.

Stems (without seeds, flowers, and leaves) were milled afterward on the laboratory mill (Retsch SM 100, Retsch GmbH, Haan, Germany) for the further analysis of chemical composition.

2.4. Chemical Compounds of the Stem

Fiber analysis included cellulose, hemicellulose, and lignin analyses in industrial hemp stems. For this analysis, the stem samples were ground on a mill for grinding plant material at the Faculty of Agrobiotechnical Sciences, Osijek, and taken to the Faculty of Food Technology in Osijek, to the Laboratory of the Institute for Process Engineering, where fiber analysis was determined.

According to Goering and Van Soest's method [60], the fibers were determined. According to Goering and Van Soest, hemicellulose is determined to be the difference between NDF (neutral detergent fiber) and ADF (acid detergent fiber).

2.5. Stem Chemical Composition

To determine the chemical elements N, P, K, and Ca, industrial hemp stem samples were dried in an oven at 105 °C for 24 h to a constant mass. After drying, the stems were ground using a laboratory mill with knives (Retsch SM 100, Retsch, Haan, Germany).

The analysis of macro elements in the stem, N, P, K, and Ca, was carried out after the destruction of the stem on the destruction block with the help of mixtures of acids (sulfuric and perchloric acid) and hydrogen peroxide, and then their concentrations were determined using atomic absorption spectroscopy, ICP–OES PerkinElmer Optima 2100 DV. Nitrogen concentration was determined using a Kjeldahl apparatus (Buchi B-324, Buchi, Flawil, Switzerland). The analysis was conducted in the Central Laboratory of the Departement of Agroecology and Environmental Protection in Osijek, Faculty of Agrobiotechnical Sciences, Osijek.

2.6. Tensile Properties of Stems

Tensile tests on stems were conducted to investigate the effect of two types of potassium fertilizers on stem stiffness and tensile strength. The effect of fertilization on the hemp stem has been demonstrated in comparison to stems without fertilization.

2.6.1. Material and Specimen Selection

Three sets of six industrial hemp samples were prepared for testing. The center part of the industrial hemp stem, which was bounded by the nodes, was chosen for stem samples. The first group of samples were steams without pre-sowing fertilization (K_0); the second group of samples was fertilized with 100 kg ha^{-1} potassium chloride (KCl) (K_1); and the third group of samples received 100 kg ha^{-1} potassium sulfate (K_2SO_4) (K_2). The samples are labeled x, y, z, with the first mark, x, indicating industrial hemp (IH) and the second mark, y, indicating potassium fertilization, which ranges from 1 to 3: K_0 is marked with 1, K_1 with 2, and K_2 with 3. The third mark, z, specifies the number of samples, which ranges between one and six for each group of samples. Tests were conducted on half of the longitudinally cut stems. Before the test, the sample's length, external diameters at three positions (ends and middle), and straw wall thickness (ends) were measured, and the average cross-sectional areas were calculated.

2.6.2. Test Setup

The material universal testing machine Zwick/Roell Z600 (manufacturer Zwick GmBH & Co. KG, Ulm, Germany) was used to load the sample under tension to determine its maximum braking force. Test management and registration of the data were conducted using TestXpert II software V3.61. Mechanical jaws with rubber inserts were used to fix the samples with capacities up to 10 kN and a load cell with a capacity of 50 kN. The test setup is shown in Figure 3. The tension in the samples is simulated by controlling the displacement of a moving crosshead at a test speed of 0.5 mm/min. The end of testing is defined when the tensile strength is reduced to 80%. The axial forces and displacements in the moving crosshead were recorded during the test. The stresses and strains in the specimen were calculated based on the measured forces and displacements.

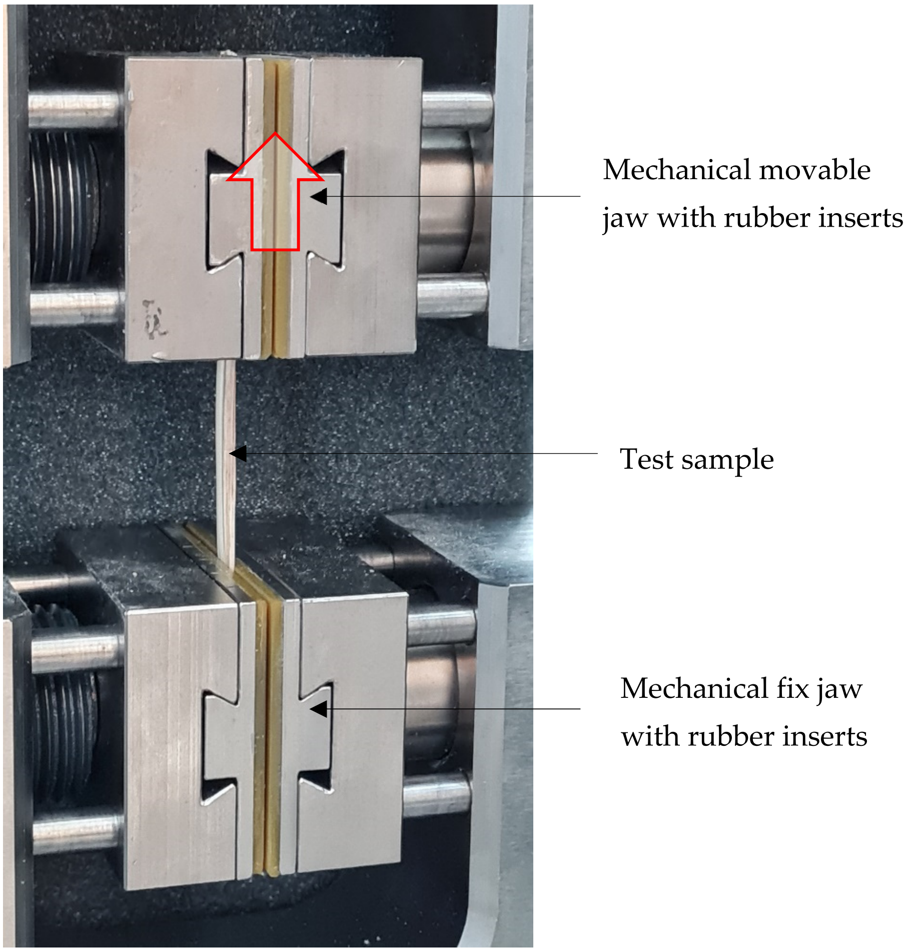

Figure 3. Test setup.

2.7. *Wetting of the Stem and Fiber Extraction*

Stems were wetted using the mod Aified method of Pasković [50] to extract fibers from the industrial hemp stem. The stems were wetted in the Memmert chamber (GmbH+Co. KG, TypICH260C, Ulm, Germany) at the Faculty of Agrobiotechnical Sciences, Osijek. The stems were cut to a length adapted to the width of the aluminum containers and the width of the chamber (50–60 cm). A load from above was used to submerge the stems at a temperature of 33 °C. Since part of the water evaporates during this process, it was necessary to top it up daily with heated water (27–28 °C). Such a procedure lasts 72 h. In this way, a large number of stalks cannot be soaked. After soaking, the stem was placed on cellulose tissues and then in a dryer at 70 °C for 24 h. After drying the stem, the fibers were separated from hurds, and the inner part of the plant stems were separated using the wooden stand, which had previously been used to separate the fibers (Figure 4). In addition, hemp hurds were manually removed from the fibers (Figure 5), and the extracted fibers were used for mixtures with the rammed earth.

Figure 4. Wooden stand for fiber extraction.

Figure 5. Industrial hemp fiber both with hurds and after removing the hurds.

2.8. Influence on Compressive Strength of Rammed Earth

Hemp fibers were built into rammed earth samples to test their influence on compressive strength. Since the industrial hemp stems were not malleable, fibers were extracted from the stems for this study to make soil mixtures. Due to the high variability in stem samples for tensile strength and modules of elasticity, fertilizations were not considered for making mixtures with rammed earth.

Namely, sample characteristics for testing the compressive strength of concrete were made: cubic samples of 15 × 15 × 15 cm and cylindrical samples 30 cm high, Φ15 cm. A similar approach was previously used to test the rammed earth's compressive strength [51]. However, even though researchers commonly test samples following a 28-day drying period, Schroeder [61] proposes a longer drying period due to the different nature of the earth and concrete. Thus, samples were tested after 12 months of curing in controlled laboratory conditions (25 ± 2 °C, RH 50 ± 5%). Further testing of samples after shorter and longer curing periods is underway and will be presented elsewhere. Yu et al. [62] reported that longer retting times also decreased the fiber strength and toughness of the flax stems.

Rammed earth samples were made from locally available soil mixed with fine sand from the Drava River. The soil mixture presented in Figure 6 was determined according to a local envelope presented in a previous work [63]. Samples were built by manually compacting each layer until the compaction of ca. 98% was reached [64]. Consecutive layers of approximately 5 cm were made, while 300 g/m^2 of hemp was added in every other layer. It was decided to add the hemp between the layers and not mix it into the soil, since achieving a uniform distribution of hemp in the mixture was impossible. A control mixture without hemp was also made to verify the impact on compressive strength.

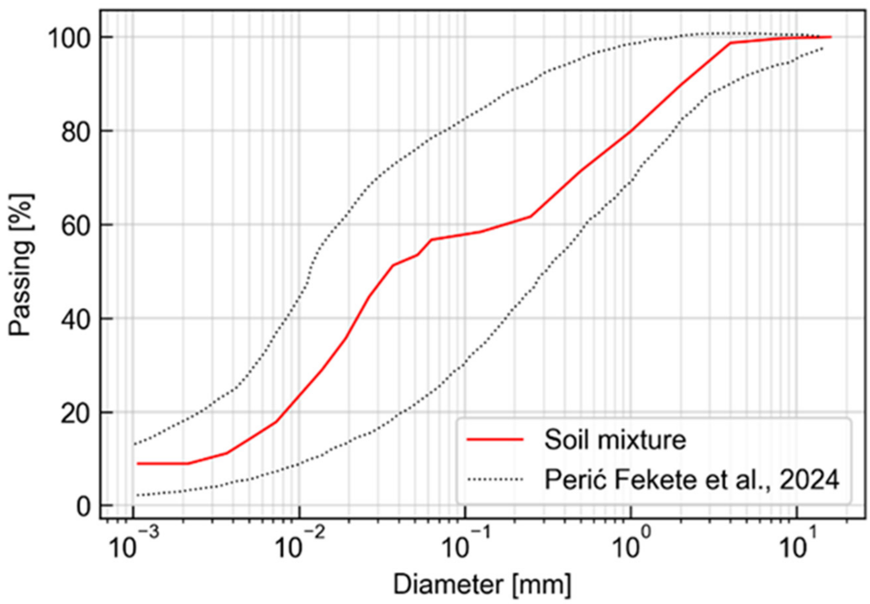

Figure 6. Particle size distribution of used soil mixture compared to local envelope [63].

Compressive strength was tested using a Shimatzu (Kyoto, Japan) AG-X testing machine with a capacity of 300 kN. The load was applied to the top of each sample using 1 mm/min displacement control. All of the samples were measured prior to testing, and minimal shrinkage (0–2.5%) after 12 months of drying was observed. Three samples per batch were tested.

2.9. Statistical Analysis

The data were statistically analyzed using SAS Enterprise Guide 7.1 [65]. An analysis of variance (ANOVA) was carried out. Differences between the means of the treatments were calculated with the LSD test used at a confidence level of 95% ($p < 0.05$).

3. Results and Discussion

3.1. Industrial Hemp Stem Properties and Chemical Composition

High air temperatures in June, with a lack of rainfall, resulted in the accelerated transition to the generative phase of growth and fertilization. Therefore, the plants remained relatively low compared to the genetic potential of the Finola variety. In this study, the morphology of the industrial hemp did not differ significantly for different potassium treatments. In the study of Finnan and Burke [66], differences in dry matter of industrial hemp appeared unrelated to the level of potassium added (0, 60, 90, 120, and 150 kg K ha^{-1}). In the present study, the K fertilization did not significantly influence ($p < 0.05$) the biomass yield, even though the effect of K on stem yield is still unclear. Several studies are available on other fiber crops. Ullah et al. [67] reported that, for ramie (*Boehmeria nivea* L.), fertilization treatment (NPK) has a positive influence on stem diameter and plant height, as compared to the control treatment. Yang et al. [68], for cotton plants, reported that K-deficient soils decreased fiber strength and fiber quality.

In this study, different K fertilizers had a significant influence ($p \leq 0.05$) on industrial hemp stem height, but stem diameter did not differ significantly throughout treatments (Table 1). The main plant nutrients, such as N, P, and K, can influence stem morphology differently. Pospišil [19] states that lack of K in industrial hemp nutrition prolonged the flowering stage for male plants, but male plants also form higher amounts of pollen. Moreover, the author states that a lack of K shortens the growth period and decreases stem height and fiber quality. In Greece, Papastylianou et al. [41] found that even though N fertilization (120–240 kg ha^{-1} N) increased industrial hemp biomass yield and stem dry matter, N fertilization did not significantly influence industrial hemp plant height. Zhou et al. [69] reported that the diameter of the industrial hemp stem was, on average, 1.6 mm, whereas in this study, the plants of the Finola cultivar had higher stem diameter. Amarasinghe et al. [70] explored the morpho-anatomical differences in hemp stems and stated that there were significant morphological variations among the 16 hemp genotypes studied and that differences affected fiber processing due to a unique pattern of fiber wedges observed in the cross-sections of the basal internodes. The authors found that stem height varied from 79.9 cm (Białobrzeskie genotype) to 215.0 cm (Tetra genotype), and stem diameter varied from 22.1 mm (Białobrzeskie genotype) to 34.3 mm (Tetra genotype). Liu et al. [71] reported that hemp fibers, which are rich in cellulose, have garnered attention as reinforcement agents in composite materials due to their low cost, lightweight nature, strong mechanical properties, and potential for sustainability and biodegradability. Thus, based on the present study, the Finola variety has great potential due to its high cellulose content.

Table 1. Analysis of variance of agronomic and composition attributes of industrial hemp stem fertilized with different potassium levels (0, 100 kg ha^{-1} KCl, and 100 kg ha^{-1} K_2SO_4).

Fertilization	No. Plants	Plant Height	Steam Diameter	Biomass Yield	N	P	K	Cellulose	Hemicellulose	Lignin
	ha^{-1}	(cm)	(mm)	(t ha^{-1})		(%)			(% Stem Dry Weight)	
K_0	29.000	88.4	3.5	18.0	0.87	0.71	1.15	57.8	11.6	10.5
K_1	36.667	56.4	3.3	16.9	0.76	0.62	1.24	58.4	11.6	10.3
K_2	30.333	68.8	3.5	17.2	0.72	0.82	1.39	59.0	11.0	10.2
Average	32.000	71.2	3.4	17.4	0.78	0.72	1.26	58.4	11.4	10.3
$LSD_{0.05}$	ns	14.0	ns	ns	0.14	0.06	0.41	ns	ns	ns

Plant nutrients varied significantly due to the K fertilizer source (Table 1). The increment of K in stem dry matter was significant ($p < 0.05$), and it was 0.09 higher with the KCl (K_1) application, and even more, by 0.24%, with the K_2SO_4 (K_2) application compared to the control treatment. Other authors confirmed higher accumulation in the stem. Iványi [72] reported that, in the year with more rainfall, the K concentration of the stem was 2.87% and in the dry year was a bit less, 2.55%.

According to chemical composition, this study's average cellulose, hemicellulose, and lignin content were 58.4, 11.4, and 10.3% of stem dry matter, respectively. Their content did not vary significantly between different K fertilizer forms. Zaman et al. [73] found that K fertilization improved stem cellulose content in rice. Other authors found similar compounds in hemp hurds and hemp fibers. Thus, Bokhri et al. [74] found 45.66% cellulose, 24.57% hemicellulose, and 21.67% of lignin for industrial hemp hurd. Salami et al. [75] stated that industrial hemp hurds from the stem were composed of cellulose 34–48%, 21–25% hemicellulose, and 17–19% lignin, and according to Liu et al. [76], hemp fibers are generally composed of 53–91% cellulose, 4–18% hemicellulose, 1–17% pectin, and 1–21% lignin.

According to the regression analysis (Figure 7), in this research, it was determined that there is a very weak relationship between stem height and seed mass per plant, with a coefficient of determination of $R^2 = 0.12$ (K_0) to 0.20 (K_1). It was determined that for every centimeter increment in stem height, the seed weight increased by 0.02 g per plant (K_0) and 0.04 g per plant (K_1 and K_2).

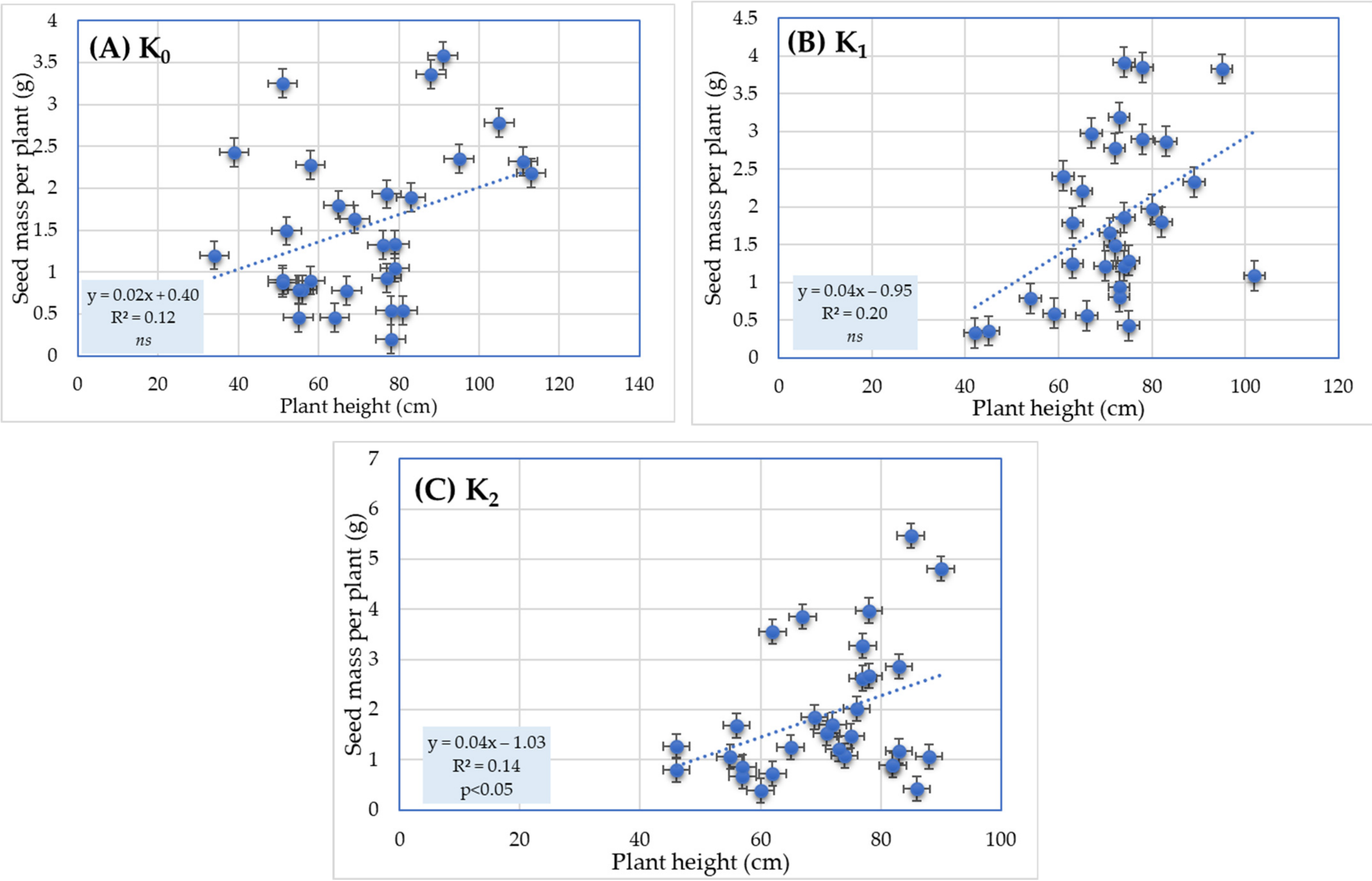

Figure 7. Scatter plot diagram of industrial hemp plant height and mass of seeds per plant regarding the K source. Error bars indicate a standard error of 5%.

3.2. Industrial Hemp Stem Stiffness and Tensile Strength

The longitudinal compressive strength of hemp stems is important for determining hemp stems (or shives) as a reinforcement for various materials [77]. Therefore, in this study, plants for stem stiffness and tensile strength were collected in the stage of seed maturity.

Tensile strength tests were performed on samples of dry industrial hemp stems following two different K treatments of fertilization (K_1 and K_2), and comparisons were made with unfertilized samples (K_0). Each group received six test samples (Figure 6). It should be noted that the experiments revealed a significant dispersion of measurement results. The test results are given in Table 2, while the diagrams of the relationship between stress and strains are given in Figure 8.

Table 2. Tensile mechanical characteristics of industrial hemp.

Sample	Max F (N)	Average Cross-Section A (mm^2)	Tensile Strength $\frac{F}{A}$ (MPa)	Average Tensile Strength (MPa)	Standard Deviation of Tensile Strength (MPa)	Young Modulus (GPa)	Average Young's Modulus (GPa)	Standard Deviation of Young's Modulus (GPa)
IH1—unfertilized								
IH1-1	646.60	1.29	501.24	331.51	151.86	28.11	21.09	13.34
IH1-2	568.59	1.28	444.21			23.85		
IH1-3	180.99	1.21	149.58			37.79		
IH1-4	290.80	1.44	201.94			4.27		
IH1-5	421.89	1.17	360.59			11.42		
IH1-6 *	773.51	1.78	434.56			14.03		

Table 2. *Cont.*

Sample	Max F (N)	Average Cross-Section A (mm^2)	Tensile Strength $\frac{F}{A}$ (MPa)	Average Tensile Strength (MPa)	Standard Deviation of Tensile Strength (MPa)	Young Modulus (GPa)	Average Young's Modulus (GPa)	Standard Deviation of Young's Modulus (GPa)
IH2—potassium chloride (KCl) fertilization								
IH2-1	545.14	1.00	545.14	388.52	132.85	38.07	32.09	9.91
IH2-2 *	71.03	1.22	58.22			20.74		
IH2-3	451.63	1.88	240.23			18.99		
IH2-4	464.12	1.35	343.79			28.23		
IH2-5	564.02	1.86	303.24			30.17		
IH2-6	433.67	0.85	510.20			45.00		
IH3—potassium sulfate (K_2SO_4) fertilization								
IH3-1	339.26	1.31	258.98	234.00	95.16	27.81	22.71	13.24
IH3-2	261.26	2.16	120.95			11.18		
IH3-3	283.05	2.15	131.65			13.06		
IH3-4	512.21	1.65	310.43			25.55		
IH3-5	295.11	1.32	223.57			28.93		
IH3-6	451.60	1.26	358.41			29.74		

* The result is not considered when calculating the average values.

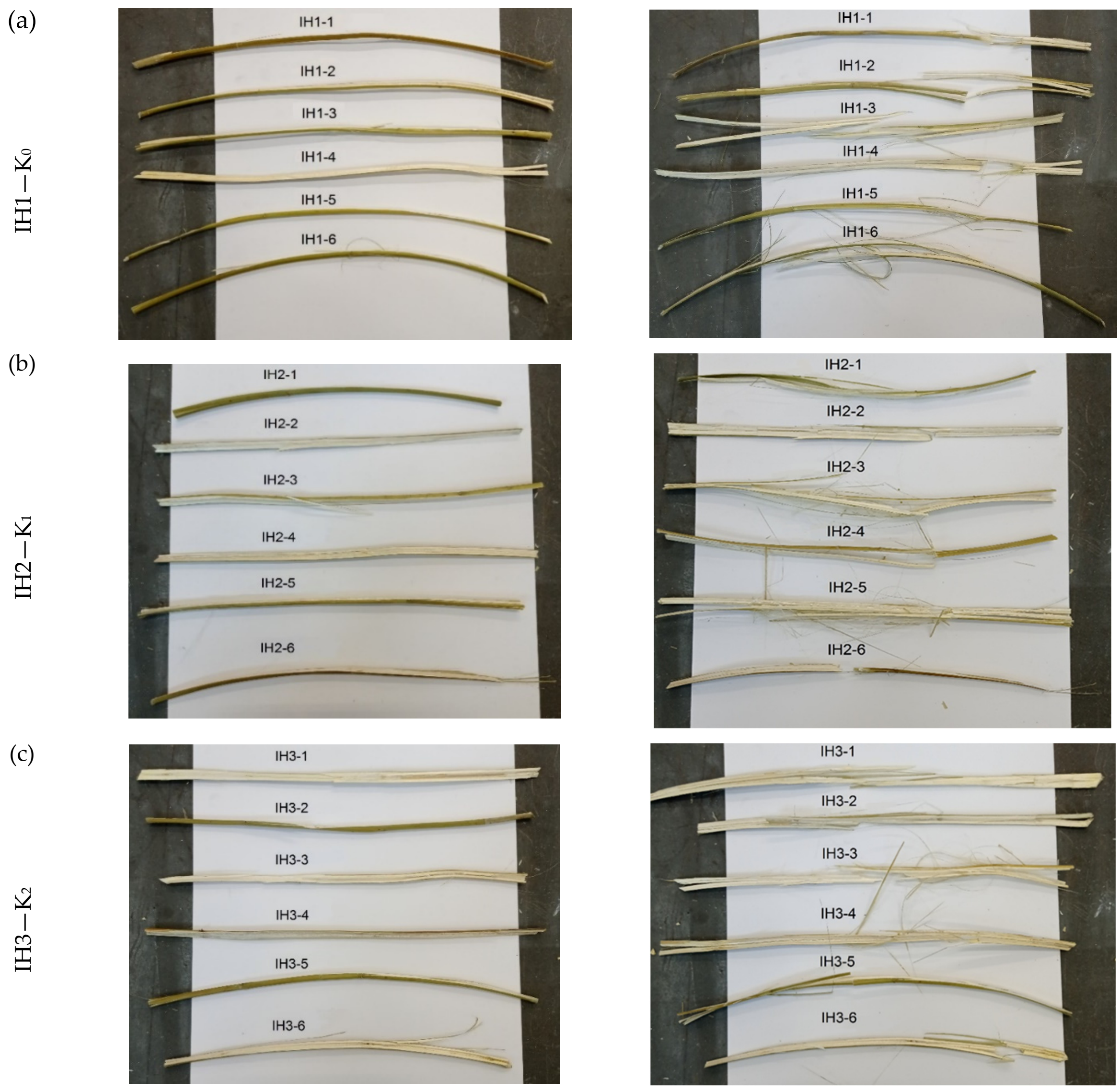

Figure 8. Industrial hemp Finola cultivar stem samples of different K treatments to determine the maximum breaking force (on the **left**) and shape of the samples after breakdown (on the **right**).

Individual samples have tensile strengths ranging from 180.99 to 568.59 MPa. This is because hemp stems are a naturally inhomogeneous material with widely varying properties. The estimation was that samples with very high or low tensile strength have measurement errors and should be excluded from the calculation. The average tensile strength of unfertilized hemp is 330.90 MPa, while that of KCl–fertilized hemp (K_1) was 389.12 MPa, and that of K_2SO_4–fertilized (K_2) hemp was 233.82 MPa.

The modulus of elasticity was determined on the basis of linear regression lines placed on the elastic part of the sigma–epsilon curve (Figure 9). The average modulus of elasticity is equal to 21.09 GPa for IH1, 32.09 GPa for IH2, and 22.71 GPa for IH3. The highest modulus of elasticity was obtained for sample IH2-6 and is 45 GPa, while the lowest value of 4.27 GPa was obtained for sample IH1-4.

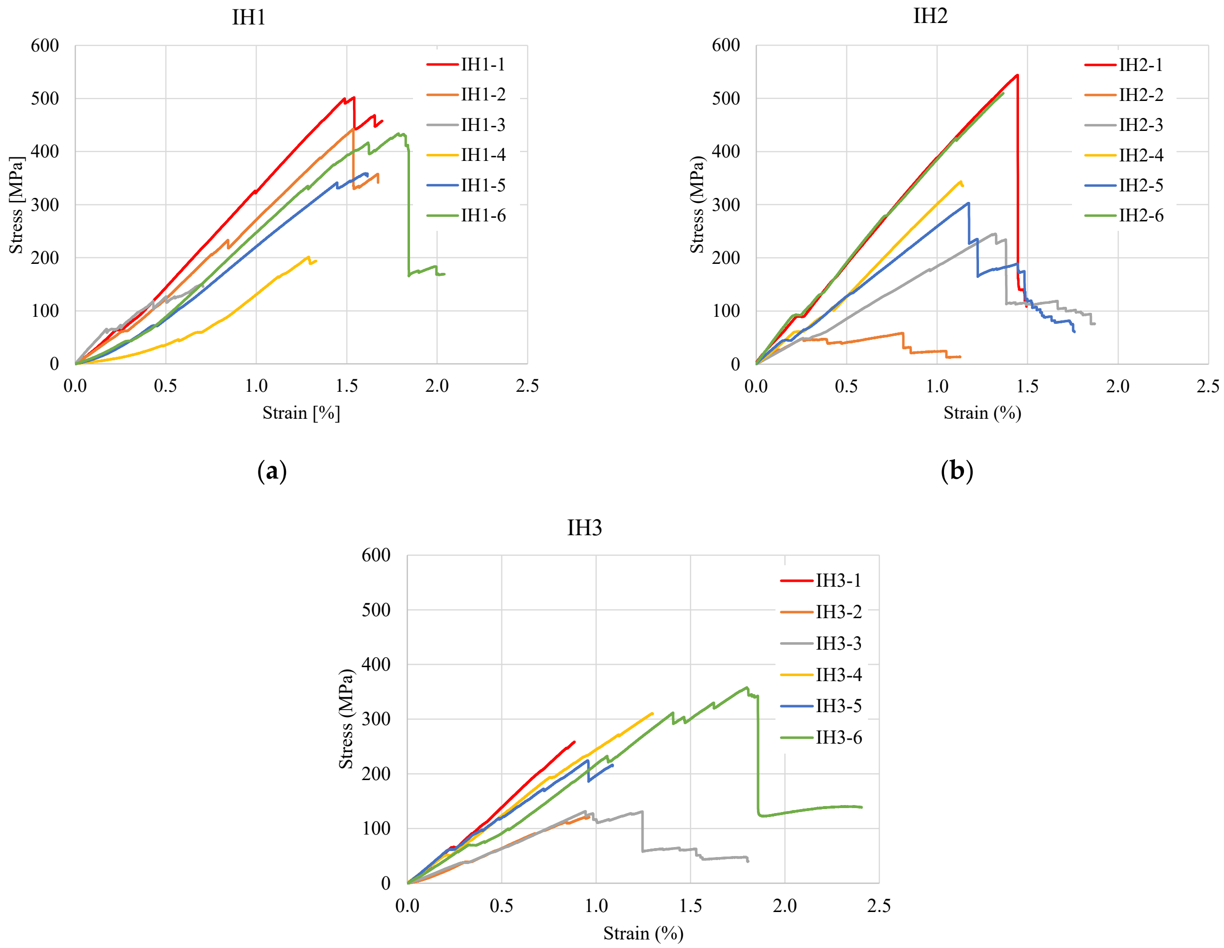

Figure 9. Stress–strain diagrams for industrial hemp Finola cultivar stem: (**a**) IH1, (**b**) IH2, and (**c**) IH3.

There are no available data on the influence of the K fertilizer source on industrial hemp stem stiffness and tensile strength. For ramie, as a fiber crop, Ullah et al. [67] reported that balanced NPK fertilization increased the braking strength of fibers (47 cN) as compared to unfertilized plants (21.6 cN). In rice plants, Tang et al. [77] stated that the tensile strength of the stem was 29.02 MPa with an elastic modulus of 1.03 GPa. Industrial hemp in our study showed much higher tensile strength and modulus of elasticity due to fiber morphology along the stem. According to Liu et al. [76], industrial hemp fibers can potentially replace glass fibers as reinforcements of composite materials due to their stiffness and failure strain tensile strength, which ranges from 200 to 1000 MPa. The growth phase of the industrial hemp plant also has an influence on hemp tensile strength and stiffness. Liu et al. [71] reported that hemp fibers harvested in the flowering stage have higher tensile strength and stiffness (950 MPa and 35 GPa, respectively) than those harvested in the stage of seed maturity (810 MPa and 31 GPa, respectively). When testing fibers on tensile strength, Berzins et al. [61] reported that tensile strength ranged from 273 MPa to 715 MPa for individual samples of industrial hemp fibers. Even though the whole stem was analyzed in our study, the results from the fibers' tensile strength are similar to our results. Amarasinghe et al. [70] stated that fiber yield and tensile strength varied among 16 different hemp genotypes and that these findings suggest that certain genotypes may be more suited for specific industrial applications based on their fiber properties.

There are limited studies of fertilization treatments on hemp stem elasticity modules. Zhou et al. [54] accentuate the importance of industrial hemp stalk due to harvest machinery's applications and designs. According to the authors, the industrial hemp stalk axis elasticity modulus was 1743.50 MPa, whereas the radial compressive elasticity modulus was 88 MPa. In our study, the Finola variety showed higher values for both parameters, which may be important for the harvest, since this cultivar is mostly grown for seeds, and farmers in Croatia do not have adequate machinery for seed and stem harvest. According to Berzins et al. [58], the modulus of elasticity of hemp fiber was varied for genotypes, e.g., for the Tygra industrial hemp genotype it was 37.9 GPa, and for the Bialobrzeskie genotype it was only 18.6 GPa. The authors also found different stem longitudinal compressive strengths ranging from 11.7 MPa (Epsilom and Woeko variety) to 26.4 MPa (Santhica 27 variety).

3.3. Soil Mixtures with Industrial Hemp

Using natural materials has been a major focus in recent years [78]. Compressive strength was tested on cubic and cylindrical samples made of soil mixture with and without hemp between the layers. The results determined for each test sample are presented in Table 3.

Table 3. Compressive strength determined on controlled and industrial hemp mixture.

Mixture	Sample	Cube				Cylinder			
		f_c [MPa]	$f_{c,av}$ [MPa]	SD [MPa]	w [%]	f_c [MPa]	$f_{c,av}$ [MPa]	SD [MPa]	w [%]
Control mixture	#1	2.76	2.65	0.12	2.12	2.05	1.71	0.41	1.93
	#2	2.67			2.12	1.81			1.95
	#3	2.52			2.20	1.25			2.03
Hemp mixture	#1	2.66	2.63	0.03	1.96	1.87	1.75	0.13	2.06
	#2	2.63			1.95	1.62			1.83
	#3	2.60			1.98	1.76			1.90

f_c—compressive strength, $f_{c,av}$—average compressive strength, w—moisture content.

It was observed that higher levels of compressive strength were on cubic samples than on cylindrical samples. However, the difference between the control and hemp mixture was not significant. Therefore, one can presume that hemp, when added between the rammed earth layers, does not influence the compressive strength of the sample. However, this thought must be verified on more samples and different material compositions. Laborel-Préneron et al. [79] wrote a review of the relevant literature regarding reinforcing earth construction with natural fibers. However, they mention the usage of hemp fibers in earthen construction, but only in compressed earth blocks and earth plasters. Hallal et al. [54] examined the influence of hemp fibers on the tensile strength of rammed earth. They proved that the addition of 0.75% and 1.25% of hemp fibers increased tensile strength by 150% to 200% in unstabilized specimens, respectively. The increase was even greater when specimens stabilized with cement and lime were considered. However, the negative effects on compressive strength that increased as the hemp percentage increase was also determined by Mabrouk et al. [80], and the shear strength of rammed earth samples reinforced with natural fibers was determined by Kaluđer et al. [57]. They recognized the positive effect of hemp and other cereal fibers on shear strength with age (i.e., after 28 days).

4. Future Prospects and Conclusions

Since changes in regulations have allowed for the use of stem and seed, this study focuses on using industrial hemp as a fast-growing renewable source of natural material for mixtures with rammed earth. This study highlights the potassium fertilizer formulation on industrial hemp stem morphology, chemical composition, tensile strength, and the possibility of using the fibers in mixtures with rammed earth. The Finola cultivar is the most common growing cultivar in Croatia because it is used for seed production. The results of this study have shown that the type of potassium fertilization has a measurable impact on the morphological and mechanical properties of industrial hemp fibers, with potential implications for their applications in sustainable construction.

Tensile strength was not significantly impacted by applying potassium fertilizers to industrial hemp stems. Compared to unfertilized samples, fertilization with potassium chloride (KCl) contributes 17.2% to the strength, whereas fertilization with potassium sulfate (K_2SO_4) significantly reduced the tensile strength by nearly 30%. Both types of fertilization have a favorable impact on stem stiffness. In the case of natural materials, it is advised to include a wider population of test samples to gain a more comprehensive understanding of their behavior, given that significant dispersion of results is obvious and that the research was conducted on a limited number of samples.

In particular, using potassium chloride (KCl) and potassium sulfate (K_2SO_4) showed different effects on the tensile strength and stiffness of hemp stalks, which may influence their performance as reinforcing material in rammed earth mixtures. The addition of hemp fibers to rammed earth layers represented a promising approach to increase compressive strength while reducing shrinkage, although further studies are needed to optimize the distribution and integration of fibers. In addition, the effects of fertilization on soil conditions were investigated. It became clear that certain sources of potassium can alter nutrient uptake and influence soil–plant dynamics. This aspect is crucial to achieving optimal plant performance and sustainable building practices.

In most cases, the stem stays in the field and then it is plowed as harvest residue, buried, or destroyed. This study shows a new approach and great potential for using the whole plant: seeds and stem. One of the possible ways to use stems is in the construction industry. Many researchers currently focus on eco-friendly materials, so this study contributes to the use of extracted industrial hemp fiber in mixtures with rammed earth. Since the knowledge about the construction of rammed earth houses is slowly disappearing because it is related to the elderly population in villages, this study is important not only for different approaches in the construction of new sustainable structures houses, but also in the reconstruction of earthen houses, which are widespread, especially in Eastern Croatia.

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